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U. S. ARMY
TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

TCREC TECHNICAL REPORT 62-80

ANALYSIS AND TEST RESULTS OF DIVISION OF POWER BETWEEN LIFT FAN AND JET NOZZLE

Task 9R38-01-020-02

Contract DA 44-177-TC-584

December 1962

prepared by:

GENERAL ELECTRIC COMPANY
Flight Propulsion Laboratory Department
Cincinnati, Ohio

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U. S. ARMY TRANSPORTATION RESEARCH COMMAND
Fort Eustis, Virginia

The engineering analysis for division of engine power between lift fan and jet nozzle was instigated to provide preliminary design estimates of weights and performance for various power division arrangements. The experimental verification of variable diverter valve door relative positioning to maintain a fixed gas generator effective nozzle area indicates a practical means of providing power division, if required, although it does not provide optimum fan lift.

FOR THE COMMANDER:

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LIST OF SYMBOLS

$A_{5.4}$	turbine diaphragm area
A_8	jet nozzle throat area
AR	aspect ratio
a_x	horizontal acceleration
a_y	vertical acceleration
C_{D_i}	coefficient of induced drag
C_{DO}	coefficient of profile drag
C_{DPF}	coefficient of planform drag
C_L	coefficient of lift
D_C	turbojet ram drag
D_L	pitch fan ram drag
D_V	lift fan ram drag
F_{GC}	turbojet gross thrust
F_{GL}	pitch fan gross thrust
F_{GV}	lift fan gross thrust
g	gravitational acceleration
K	drag polar, $\left(C_{D_i}/C_L^2\right)$
m	mass
Q	dynamic pressure, $\left(\frac{1}{2}\rho V^2\right)$
R	flight path radius
S_{PF}	planform area
S_W	wing area
S_x	horizontal distance
S_y	vertical distance
t	time
t_d	time delay (valve operation)
$T_{5.1}$	gas generator discharge temperature
t_m/C	mean aerodynamic thickness to wing chord ratio
V	velocity
V_P	aircraft flight velocity
V_{stall}	aircraft stall velocity
$W_{5.15}$	gas generator discharge flow
$W_{5.4}$	fan turbine flow
W_G	aircraft gross weight
x	horizontal direction
y	vertical direction
α	angle of attack
β	lift fan louver angle
θ	pitch fan orientation angle with respect to aircraft longitudinal axis
ϕ	flight path angle
ρ	density (air)
ω	angular velocity

INTRODUCTION

In the transition from VTO to horizontal flight using the General Electric X353-5 type propulsion system, power must be switched from the lift fan to the jet nozzle. This is done by means of the diverter valve.

Rapid changes in power distribution approaching the instantaneous diverter valve switch case may pose aircraft control problems due to rapidly changing forces and moments. A gradual change of power between the lift fan and the jet nozzle should greatly reduce the resulting rate of change of these quantities and therefore the control moments required to keep the aircraft on a prescribed flight path.

In this report three methods of accomplishing this gradual power transfer are considered. Two methods require little or no modification of the existing X353-5 lift fan system. The third method requires some modification of the jet nozzle and fan scroll.

METHODS OF OBTAINING FLOW SPLIT

Three methods of achieving flow split between the turbojet nozzle and lift fan turbine were considered. They are:

1. Uncompensated (gas generator discharge effective area not maintained).
2. Diverter valve area compensation.
3. Nozzle area compensation.

UNCOMPENSATED

With uncompensated operation the turbojet and fan turbine nozzle areas are fixed as is the diverter valve door linkage. The angle between the two diverter valve doors is therefore fixed. As the diverter valve is actuated to achieve the desired flow split, it exposes the gas generator to a larger exit area, reducing the back pressure. To keep the gas generator from overspeeding, the fuel control then reduces the fuel flow, reducing the gas generator discharge temperature. With discharge pressure and temperature reduced, the available horsepower to the fan is reduced. The resulting lift and thrust are therefore less than for the corresponding flow split with some type of area compensation. The estimated performance for this case assumes no additional pressure loss in opening the diverter valve. The advantage of this method is that no extra hardware is required and therefore there is no added weight penalty. Figure 1 shows a comparison of the percent of lift and thrust obtained with the three methods of area compensation as a function of flow split.

DIVERTER VALVE DOOR COMPENSATION

If the gas generator discharge temperature and pressure could be maintained, the lift and thrust at any given flow split would be increased. To maintain discharge temperature and pressure, the gas generator must "see" a constant discharge area as the diverter valve is actuated. One method of achieving this is to actuate the two diverter valve doors separately, using a separate actuator for each door. The actuators would be programmed so that the total effective flow area to the tailpipe and fan turbine scroll remains constant. In estimating the performance shown in Figure 1, the following assumptions are made:

1. The flow coefficient characteristics at the fan turbine diaphragms are unaffected by the throttling of the valves. This assumption is required since flow split is determined by continuity considerations at the fan turbine diaphragms and jet nozzle. With temperature known and a desired fan turbine flow selected, the total pressure at the turbine inlet required to pass this desired flow can be determined using turbine characteristics.
2. To completely determine discharge areas for continuity purposes, the jet nozzle flow coefficient characteristics are also assumed to be unaffected by the throttling of the valves. This implies that the jet nozzle flows full. The only reduction in nozzle flow area is then due to the normal flow coefficient which is a function of the total to static pressure ratio at the nozzle throat. If in the actual case both the scroll and jet nozzle had lower flow coefficients, better performance would be obtained from both the fan and jet nozzle.
3. The above assumption implies that the valve can be positioned to deliver the desired turbine inlet flow at the pressure loss obtained by balancing the turbine. Performance at flight speeds of 0, 80, 100, 120, and 150 knots with a louver angle of 40° is shown in Figures 2 through 6.

The weight increase due to the additional diverter valve door actuator is estimated to be 8 lbs. per diverter valve.

NOZZLE AND SCROLL AREA COMPENSATION

Another method of maintaining a constant gas generator discharge effective area is to vary the fan turbine scroll and jet nozzle areas as different flow splits are desired. With this method the diverter valve door linkage is fixed, as for the uncompensated case. The Mach numbers in the tailpipe and fan turbine ducting for flow split are less than when full flow is going through either one. The pressure loss should then also be less. The performance shown in Figure 1 for this method assumes that the increased pressure loss due to the adverse flow conditions over the partially opened diverter valve doors makes up for this decreased duct loss. Since the throttling loss associated with the diverter valve door method of compensation is not present with this method, the predicted performance is higher. This is shown in Figure 1.

The jet nozzle and fan turbine diaphragm area modulation performance curves on Figure 1 assume that both areas are completely variable from zero to 100% flow in either direction. Practically, this is not the case, although jet nozzles can be made to approach this condition.

Description of Jet Nozzles

Jet nozzles suitable for this application must have a high ratio of maximum to minimum throat area. Four nozzles with this characteristic are shown in Figures 7 through 10. They are:

1. Two-flap
2. Two-flap square
3. Clamshell
4. Plug nozzle with flap area variation.

The double-flap nozzle consists of two sets of movable flaps. The first set is similar to that of the plug-flap nozzle. The second set is pinned to the first set. The flap motion is caused by a linkage which responds to the motion of the actuating piston. Alternate flaps contain a gear, so that piston motion causes them to deflect inward, while the remaining flaps are deflected outward. This permits the flaps which deflect inward to close further than would otherwise be possible. The components can be sized to give any desired area ratio. The motion of the fold-out flap can be regulated to close over the fold-in flaps, to minimize leakage.

The double-flap square nozzle is, as the name implies, a square nozzle with two movable sides. These doors are hydraulically actuated. Seals between the movable and fixed sides prevent leakage.

The clamshell nozzle consists of two doors, or shells, which cover the spherically shaped exhaust section. The motion of the hydraulic piston actuator causes the actuator arm to rock about its pinned support, thus moving the clamshell doors. Seals between the shell and inner wall prevent leakage.

The plug-flap nozzle consists of a fixed plug and a set of movable flaps. The variable discharge area is obtained by deflecting the hinged and inter-locked flaps using the hydraulic actuator piston. The plug permits a very small discharge area to be obtained without excessive flap deflection.

Description of Scroll Area Control Methods

Three methods of fan turbine scroll area modulation were investigated. They are:

1. Sliding plate
2. Variable turbine diaphragms
3. Scroll butterfly valves (two or four per fan)

How closely the actual performance of the lift fan using scroll area modulation approaches the top fan performance curve of Figure 1 depends on how closely the scroll area modulation approaches the completely variable case (zero to 100% scroll area available in infinitely small steps).

If a horizontal plate sliding over the nozzle diaphragms is used to achieve scroll area modulation, the nozzle partitions coverable by the plate can be considered completely variable. A small loss in efficiency would result when any individual turbine nozzle was partially covered, but this effect is small since there are so many individual nozzles and only one is partially covered at any one time. Mechanically, however, it is not practical to make the plate cover the entire scroll. The portion of the scroll not covered by the plate will be an uncompensated area when the flow to the fan turbine is less than that required to fill this uncovered area. Figure 11 shows a comparison of lift fan performance for various methods of area modulation. Curve ABC is the completely variable case. Curve H is for diverter valve door area control. If the sliding plate covers 60% of the scroll area, curve ABD would result. The D portion of the curve is uncompensated. The deviation of the actual performance from the AB portion of the curve is neglected. The sliding plate provides good area modulation but is heavy and therefore provides a range penalty on an aircraft of the ASP613B type (see Table 1). The ASP613B airplane is shown in Figure 13.

Individual nozzle partitions can also be made variable to achieve scroll area modulation. Neglecting leakage, the performance results will be the same as for the sliding plate. If all nozzle partitions are not variable, an uncompensated area will result (portion D of curve ABD). The deviation of the actual performance from the curve AB due to poor flow angles on an individual, partly closed partition is neglected because of the number of

partitions present and the fact that only one partition per scroll segment is being closed at a time. Again, while performance is good, the weight penalty and accompanying range penalty are significant.

Butterfly valves are another method of achieving scroll area modulation. The more valves in the system, the closer the actual performance will approach curve ABC in Figure 11. If one valve is used and placed at the scroll inlet, the fan performance is approximately the same as for diverter valve door area control. When the valve is located further into the scroll, the area between the scroll inlet and the valve becomes uncompensated when the fan turbine flow is not enough to fill the available area at military rated gas generator conditions. If one valve is placed 40% of the way into the scroll, the performance is given by curve ED of Figure 11. As before, portion D is the uncompensated operation. Along portion E, the butterfly valve is being positioned to maintain the scroll area reflected back to the gas generator proportional to the fan turbine flow, so that the gas generator remains at military rated operation. To do this the valve opens and throttles the flow less as the fan turbine flow increases.

If a second butterfly valve is now added at the 70% flow point in each scroll segment, the fan performance is represented by curve FGD in Figure 11. Note that it is considerably improved over that obtained using only one valve per scroll segment. This is because along curve G the downstream valve is closed so that portion of turbine between the two valves is more efficient. When the first valve is completely open and the second valve is closed, no throttling is taking place and the open portion of the scroll is operating at full efficiency. This point therefore lies on the ideal curve, ABC. As the second valve is opened, the scroll segment between the valves remains filled and therefore at operating efficiency. The performance loss incurred in opening the second valve is similar to those incurred in opening the first valve.

The weight and range penalties involved in using butterfly valves to obtain scroll area control are shown in Table 1. Note that from Figure 11 two butterfly valves involve at most a 2-3% lift penalty during compensated operation compared to the other two methods of scroll area control, and also involve about one-half the weight and range penalties.

The penalty associated with the scroll area control must be added to that due to the need for a variable jet nozzle. Using two butterfly valves per scroll segment (four per scroll) and a two-flap jet nozzle, the total decrease in mission radius is 2.62%. The heaviest methods of scroll and jet nozzle area control, the plug nozzle and sliding plate, impose a 5.32% decrease in mission radius.

Using the diverter valve doors to maintain constant gas generator discharge effective area entails a range decrease of only 0.32%. The comparative lift performance penalty is shown in Figure 11.

FULL-SCALE DIVERTER VALVE DOOR AREA COMPENSATION TEST

As specified in the contract, a full-scale static test was run in the Evendale VTOL Test Facility to verify the estimated performance obtained using diverter valve compensation. For this test the diverter valve doors were actuated separately, a few degrees at a time.

Figure 12 shows the data obtained superimposed on Figure 1. The engine thrust data lie above the predicted curve for the diverter valve compensated case. This is because the predicted curve assumes the nozzle is flowing full, while physically this was not true. The diverter valve door was apparently acting as the nozzle. This tends to simulate the nozzle area compensated case. Additional pressure losses occur due to the inefficiency of this nozzle and any disturbed flow from the second door. As a result, the performance only approaches that estimated for nozzle area compensation. The scatter which is evident in the thrust ratio points may be indicative of unstable flow conditions in the valve and tailpipe. All data are corrected to a common gas generator discharge temperature.

Fan lift ratio data agree well with the predicted curve for diverter valve compensation (separately actuated doors). The flow through the scroll closely simulated that used in obtaining the predicted curve. The fan turbine diaphragm area was not variable, and, except for the 17.2% flow point, was probably flowing full.

TABLE 1

WEIGHT INCREASES AND CHANGE IN MISSION RADIUS
FOR VARIOUS MEANS OF AREA CONTROL

	Weight Increase (per gas generator or fan) pounds	Change in** Mission Radius percent
Jet Nozzle*		
1. Two-Flap	+ 32	- 1.28
2. Two-Flap Square	+ 42	- 1.68
3. Eyelid	+ 34.5	- 1.38
4. Plug Nozzle with Flap Variation	+ 61	- 2.44
Fan Turbine Scroll		
1. Butterfly Valves (two per scroll)	+ 28	- 1.12
2. Butterfly Valves (four per scroll)	+ 33.5	- 1.34
3. Variable Nozzle Diaphragm	+ 60	- 2.40
4. Sliding Plate	+ 72	- 2.88
Diverter Valve Door Control	+ 8	- 0.32

* Increase based on a conical nozzle weighing 6 pounds.

** The change in mission radius assumes a constant take-off gross weight since design take-off lift is unaffected by method of area control.
(All mission radius changes are to same base).

TRANSITION ANALYSIS

CALCULATION PROCEDURE

A digital computer program for the IBM 7090 EDPM was written to aid in analyzing and comparing transition performance. The Fortran language was employed.

Although the program was prepared principally for a VTOL lift fan airplane configuration, the techniques are applicable to direct lift and lift/thrust configurations with appropriate modifications.

The program is an iterative integrating balance of the forces shown in Figure 14. Aircraft and powerplant characteristics are input. Desired transition path is specified by inputting flight path angle versus horizontal distance. In addition, a wind velocity may be introduced (affecting ground distance covered and therefore centrifugal force). Initial flight velocity may also be introduced. In the stalled wing regimes, aircraft attitude must also be specified. Minimum and maximum values as well as maximum rates of change of louver vector angle and unstalled angle of attack must also be specified. As outputs, angle of attack, velocities, accelerations, and direction of principal thrust vector are determined.

The aircraft used for this study is the ASP 613 B shown in Figure 13. Table 2 is a list of applicable aircraft parameters.

The transition has been broken down into five regimes, these are:

- I Vertical climb
- II "Heel-over" - the change from vertical (or almost vertical) to horizontal (or almost horizontal) flight, when the wing becomes effective at the end of this regime.
- III Acceleration on fans - the aircraft is accelerated up to the appropriate flight velocity for diverter valve switching.
- IV Diverter valve operation.
- V Acceleration on turbojets.

The forces acting during each regime are shown in Table 3. The equations of motion are given in Figure 14.

The assumptions made are as follows:

1. The forces necessary to generate the required control moments (to change or maintain aircraft attitude) are not taken into account at this time, and it is assumed that they will not significantly change the results.

2. It is assumed that the ASP613B aircraft used in this analysis is a representative VTOL fan-in-wing aircraft and that the results of this analysis are applicable to similar type aircraft of the same lift power loading and wing loading.

3. It is assumed that the transition takes place out of ground effect.

4. It is assumed that transition takes place at a constant (military) power setting.

5. It is assumed that the lift fan exit louvers move rearward only, during transition from vertical to horizontal flight.

6. During the flight regimes in which the wing is aerodynamically ineffective, (regimes I and II), the drag is based on the aircraft projected planform area, using an assumed drag coefficient of 1.2.

7. Aerodynamic interactions have not been considered in the initial work, although provisions have been made for incorporation of both lift and drag effects.

8. Engines, diverter valves, and fans are so coupled that each gas generator provides half power to each fan. The scroll of each fan is physically divided to accept power from both engines independently.

TABLE 2

ASP 613 B AIRCRAFT DEFINITION
(shown in Figure 13)

length	41.83 feet	S_W	255 square feet
span	31.00 feet	S_{PF}	425 square feet
height	13.75 feet	C_{DPF}	1.2
W_G	14,500 pounds	AR	3.1
t_m/C	14 % root, 10% mean aerodynamic chord, 6 % tip		

with main gear retracted and nose gear out, aircraft data is:

	without flaps		with flaps
C_L	1.2 @ $\alpha = 9^o$	C_L	1.8 @ $\alpha = 9^o$
$\frac{d\ C_L}{d\ \alpha}$	0.105	$\frac{d\ C_L}{d\ \alpha}$	0.120
K	0.115	K	0.160
C_{DO}	0.0165	C_{DO}	0.0170
V_{stall}	107 knots = 180.8 feet per seconds	V_{stall}	88 knots = 148.5 feet/sec.

The powerplants are two GE CJ610 gas generators driving two X353-5 size lift fans designed for 8,035 lbs lift per fan and one 1,920 lb design lift pitch fan located in the nose. Each lift fan gives 7,240 lbs nominal lift when the gas generators are delivering design flow to the pitch fan.

TABLE 3

FORCES CONSIDERED IN THE VARIOUS TRANSITION REGIMES

Symbol	Force	I	II	III	IV	V
ma	inertia force	x	x	x	x	x
W_G	weight	x	x	x	x	x
$mR\omega^2$	centrifugal force	x	x	x	x	x
F_{GC}	turbojet gross thrust				x	x
F_{GV}	lift fan gross thrust	x	x	x	x	
F_{GL}	pitch fan gross thrust	x	x	x	x	
D_C	turbojet ram drag	x	x	x	x	x
D_V	lift fan ram drag	x	x	x	x	
D_L	pitch fan ram drag	x	x	x	x	
$C_{DPF}\ S_{PF}\ Q$	planform (flat plate) drag	x	x			
$C_{DO}\ S_W\ Q$	base (zero lift) drag			x	x	x
$K\ C_L^2\ S_W\ Q$	induced drag (drag due to wing lift)			x	x	x
$C_L\ S_W\ Q$	wing lift			x	x	x

RESULTS

Regime I

Figures 15 and 16 pertain to the vertical climb portion of the transition and show the distance-speed-time relation assuming that the aircraft breaks ground with the engines at military power setting. The limiting vertical velocity is seen to be about 31 fps. Flaps do not change planform area, and a planform drag coefficient of 1.2 is assumed. Although many operational transitions may not begin with a pure vertical rise, these curves are included since this type of initial transition flight path may

be necessary under certain operational conditions and does represent pure VTO flight.

Regime II

Figures 17 through 19 describe one possible flight path in the change from vertical flight (wing negatively stalled) to unstalled wing flight (almost horizontal). In this case the aircraft has been held at a zero attitude angle, so the angle of attack is the negative of the flight path angle until the wing unstalls. It is in this flight regime that the equation of motion is highly nonlinear due to the effects of centrifugal force. This centrifugal force places a limit on the rate at which the flight path angle may decrease, depending upon the flight speed. During this "heel-over" maneuver, centrifugal force acts to hold the aircraft up in the vertical direction and back (decrease acceleration) in the horizontal direction. If, along a prescribed flight path, the flight path angle decreases too rapidly, the lift fan exit louvers must move rearward to decrease fan lift. When the flight path levels out (centrifugal force dies out), the louvers are too far rearward to support the aircraft. Also, the faster the flight path angle decreases, the higher the vertical deceleration.

If the flight path angle decreases too slowly, the aircraft will not pick up flight speed very rapidly since the large planform drag is present.

In the flight path shown, the wing unstalls when the exit louver angle is about 22°. The louvers are then swung rearward at a constant rate (degrees per second) to their maximum setting of 40° to obtain horizontal acceleration. Swinging the louvers at one degree per second, the aircraft reaches a flight speed of 164 fps (97 knots) before the louvers reach 40°. By swinging the louvers faster after the wing unstalls, the time to diverter valve operation velocity may be reduced a few seconds. A 4°/second swing rate reduces the time about two seconds.

Regime III

The aircraft acceleration to valve operation flight speed is shown in Figures 20 through 22 for both with and without flaps. These curves can be used to determine the time to reach valve operation flight speed and the angle of attack and available acceleration at any valve operation flight speed.

Regime IV

The diverter valve operation portion of the transition maneuver is described in Figures 23 through 33. Two methods of valve operation have been examined with variations in each as follows:

(a) Instantaneous valve operation

(1) simultaneous

(2) sequential

(b) Controlled valve operation

(1) simultaneous

(2) sequential

The instantaneous operation assumes that the valve door closing occurs in zero time. In the simultaneous operation, both valves are converted at the same time. Time delays of 5, 10, and 15 seconds have been assumed for the sequential method.

Fan thrust and drag have been assumed to decay exponentially for an instantaneous valve operation with a time constant of one second for thrust and two seconds for drag.

In the controlled valve method it has been assumed that the two doors in each diverter valve are modulated such that the gas generator "sees" a constant discharge area during operation and thus maintains its speed and temperature and, therefore, power output. Simultaneous controlled operations of 5, 10, and 15 seconds duration have been investigated as well as sequential valve movements of the same duration. With sequential operation, the closure time for both valves was always equal. (If the first valve took 10 seconds to close, so did the second. If the first valve took 15 seconds to close, so did the second.) The second valve operation was never begun until the first valve operation had been completed, although a five-second dead time between operations was also analyzed. In all cases the flow split between the fan turbine and the jet nozzle was assumed to vary linearly with time. No changes or modulation of fan turbine scroll area has been assumed. It has been assumed that a controlled valve operation of 5 or more seconds duration may be analyzed as a steady-state phenomenon, i.e., stored energy effects in the fan can be neglected.

With respect to the controlled valve operation, it is probable that test data applicable to the crossflow-throughflow velocity ratios may indicate substantial performance differences over the assumptions used in this study, which were based on static tests.

(a) Instantaneous Operation

Figure 23 applies to instantaneous diverter valve operations. Figure 23 shows the effect of flight speed on the change in angle of attack that must occur during and immediately after instantaneous valve operations. The flight speed scale applies to the upper line. If the first diverter valve is switched at the speed indicated and the second valve switched after the time interval indicated, the change in angle of attack associated with each operation is read on the ordinate. Since the aircraft accelerates with one valve switched, longer time delays to the second valve operation result in higher flight speeds at the second valve operation and, therefore, smaller required changes in angle of attack to maintain the aircraft in a level flight path. The higher the flight speed at the first valve operation, the smaller the changes in angle of attack associated with operation of both valves. The curve shows only the results of sequential operations. The corresponding lines for simultaneous valve operations show about twice the change required by the first valve operation shown for the same flight speed. It thus appears that the amount of horizontal tail movement required per unit time to trim the aircraft during diverter valve operation (if this is the trim mechanism used) can be substantially reduced by utilizing sequential rather than simultaneous valve operation. It also shows that, provided the trim control is available, the first of sequential valve operations may begin below aircraft stall speed since horizontal acceleration is available with one diverter valve switched.

An important assumption is involved in this consideration, i.e., that fan performance at high flight speed does not change markedly under half power operation.

Figures 24 and 25 show angle of attack versus time measured from the beginning of the first valve operation for two different initial flight speeds. Delay times between sequential valve operations of 5, 10, and 15 seconds are shown. The angle-of-attack changes due to diverter valve switching are dashed because their exact shape is not precisely known. The turbojet thrust has been assumed to act instantaneously after the diverter valve operation, while actually a delay time of about 1/4 second to full thrust is present. Also, since calculation intervals of 1/2 second were used, this will not show up.

As shown in Figure 23, as the delay time for the second valve operation increases, the required change in angle of attack decreases. Also, note the smaller required changes in angle of attack associated with increased flight speed.

Figure 26 again shows the effect of flight speed on angle of attack during valve operation. Flight speeds of 160, 180, 217, and 240 fps are shown for a delay time of 10 seconds.

Figure 27 shows velocity versus time measured from the first valve switching for instantaneous valve operations. The turbojet thrust is practically constant over the given flight speed range and results in an acceleration of about 1/3 g with both diverter valves switched.

(b) Controlled Operation

Figures 28 through 33 apply to controlled diverter valve operations of 5, 10, and 15 seconds duration per operation.

Figures 28 through 30 show angle of attack versus time measured from the beginning of the first valve operation for each of the valve closure times mentioned. Various delay times are also shown. Flight speed is 217 fps and the aircraft is without flaps.

As the closure time increases, the slope of the curves decreases, but the change in angle of attack for simultaneous valve operations increases. This is because the aircraft decelerates during simultaneous controlled operations (see Figures 31 through 33). At the same flight speed, this is not the case for sequential valve operations. Sequential valve operations require much more gradual changes in angle of attack, the curves becoming flatter as the closure time increases. Delaying closure of the second valve after the first has finished closing is seen to flatten the curves still further.

Figures 31 through 33 show flight speed versus time associated with Figures 28 through 30. The trends mentioned above are evident. The steep parallel protions of the curves are where both turbojets are in the cruise mode.

Regime V

The acceleration on the turbojet portion of the transition is shown with the diverter valve switching curves. As long as the aircraft is above its stall speed and has positive acceleration in the direction of flight, the transition maneuver can be considered completed.

CONCLUSIONS AND RECOMMENDATIONS

Figures 23 through 33 show the advantage to be gained from controlled sequential flow splits. The required change of angle of attack and therefore rate of change of angle of attack are much less than for instantaneous power changes and also less than for simultaneous controlled power changes. In addition, for sequential controlled operation, flight speed does not decrease from the value at the beginning of diverter valve operation, but remains fairly constant, rising slightly. Both these trends should reduce control moments required during the transition maneuver.

The diverter valve door method of area control appears to be the most acceptable means of achieving controlled flow splitting during transition. It is mechanically simple, requiring only an additional diverter valve door actuator and linkage. Although performance is not as good as for the nozzle and scroll area control method, the weight penalty and, therefore, the range penalty are only about 1/3% compared to 2 to 5% for the latter method. In addition, the diverter valve door method of modulating the flow split does not rely on the engine controls to keep the gas generator from overspeeding as does the uncompensated case. Full-scale hardware tests showed lift performance to be as predicted and thrust performance to be better than predicted. Force balance transition analysis using predicted performance resulted in acceptable transition performance.

It is recommended that if control considerations do not preclude it, simultaneous instantaneous diverter valve operation be utilized. It is possible that the power required for the tail motion to maintain aircraft trim will be excessive due to the large changes in moments accompanying simultaneous instantaneous diverter valve operation. In this case it is recommended that sequential instantaneous diverter valve operation be used. In both methods of operation, the engine control system will be required to prevent significant gas generator overspeed during the "instantaneous" diverter valve operation, during which time the gas generator experiences a larger discharge effective area. It is also possible that the delay time between diverter valve switches (for a system containing two diverter valves, like the one shown) required to reduce the control problem to an

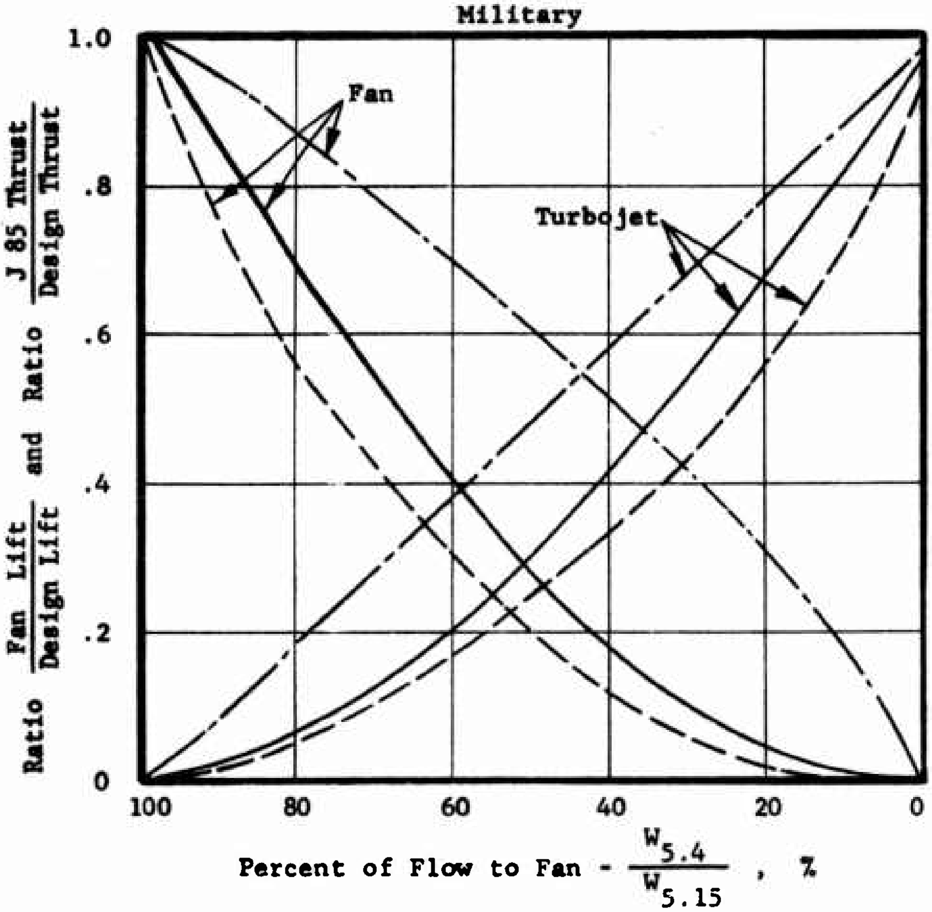
acceptable level is long enough that the aircraft gains too much flight speed between diverter valve switches. This causes high vibratory stresses in the fan attachments. If this occurs, even when the first diverter valve switch is made at the lowest safe flight speed, it is recommended that sequential controlled power transfer be adopted using the diverter valve door method of area compensation.

It is further recommended that since aircraft transition characteristics vary, the relative merit of various flow splitting devices should be re-evaluated for each aircraft studied.

Sea Level Static

$\beta = 0^{\circ}$

Military



CASE	A_8	$A_{5.4}$	$T_{5.1}$	CURVE LEGEND
Area Compensated	Variable	Variable	Maintained	——-——--
Diverter Valve Doors Operated Separately	Fixed	Fixed	Maintained	————————
Diverter Valve Doors Operated Together	Fixed	Fixed	Maintained	— — — —

COMPARISON OF THREE METHODS OF AREA COMPENSATION

Figure 1 - Divided Flow Study

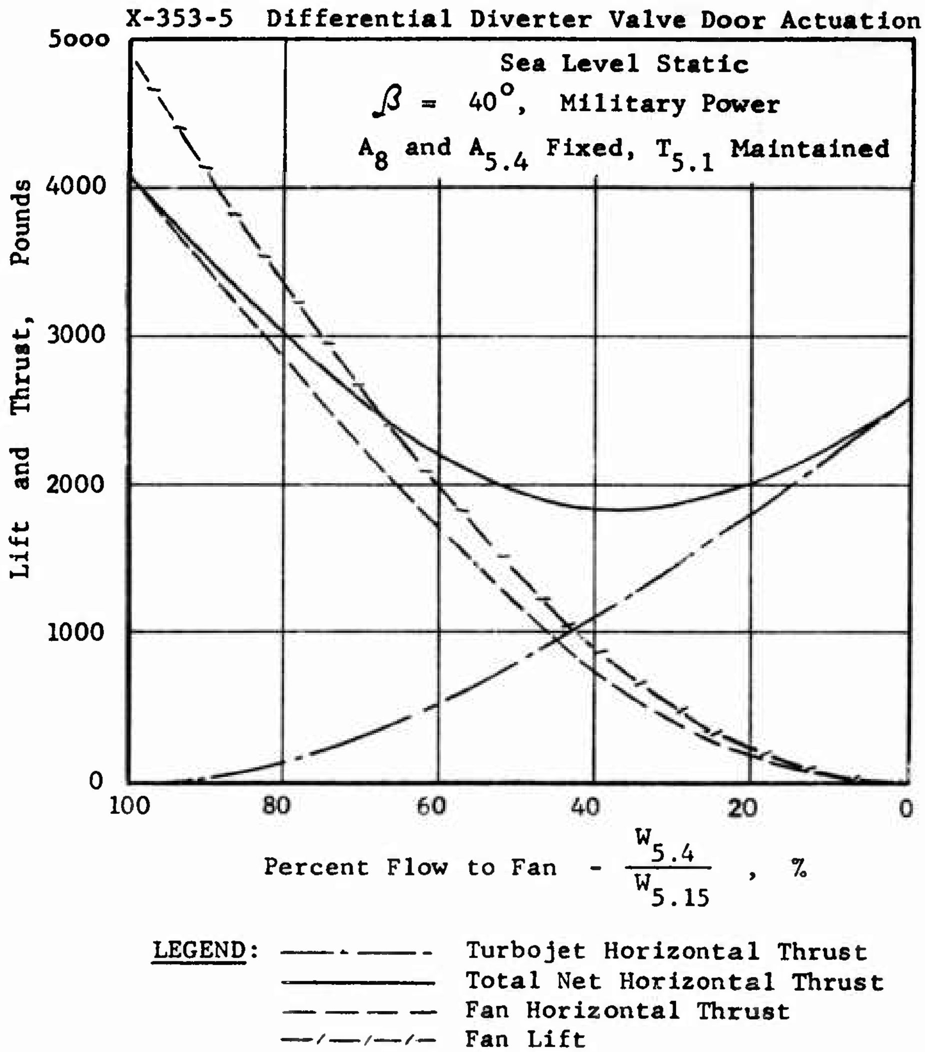


Figure 2 - Divided Flow Study

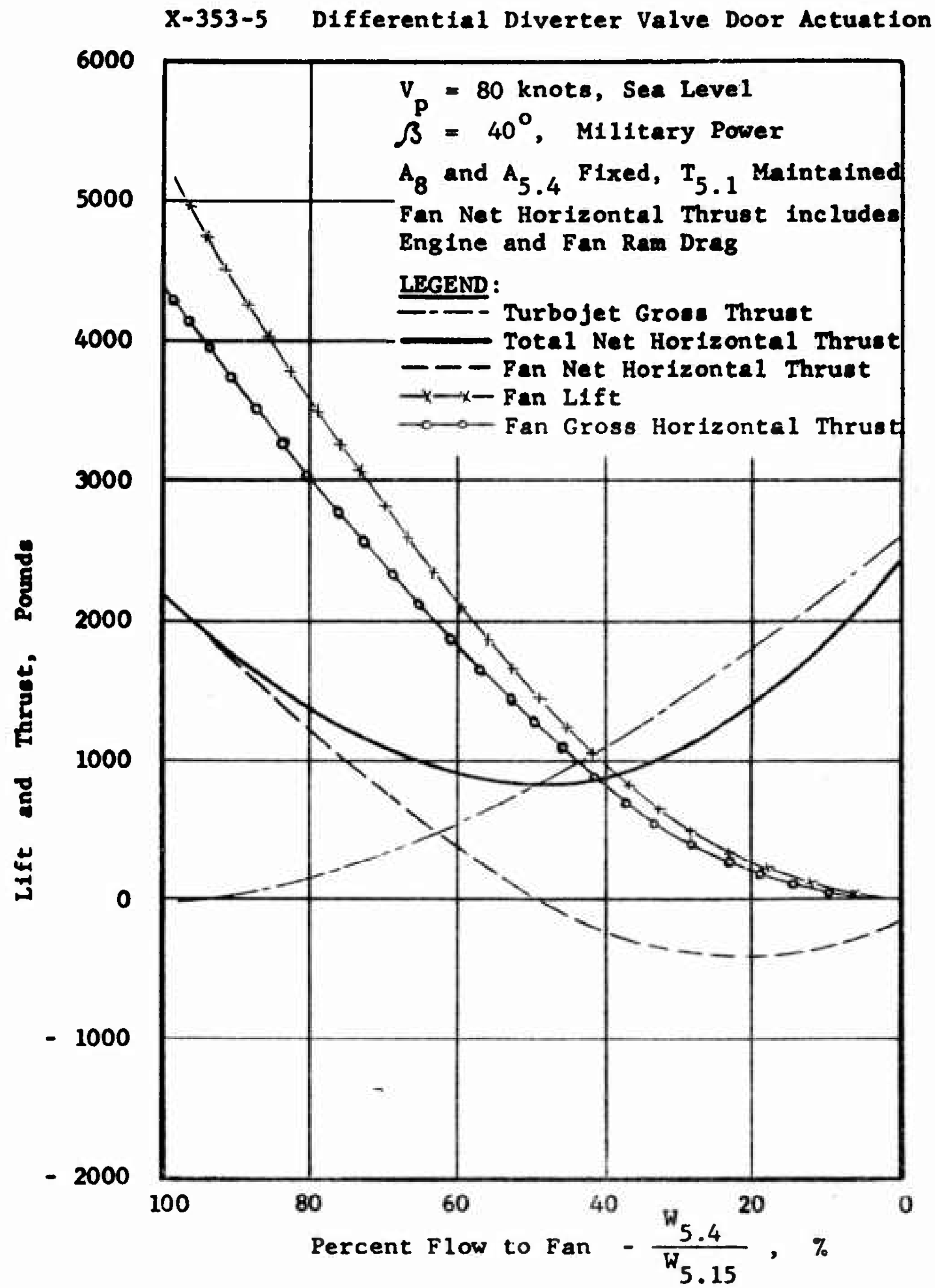


Figure 3 - Divided Flow Study (V_p = 80 knots)

X-353-5 Differential Diverter Valve Door Actuation

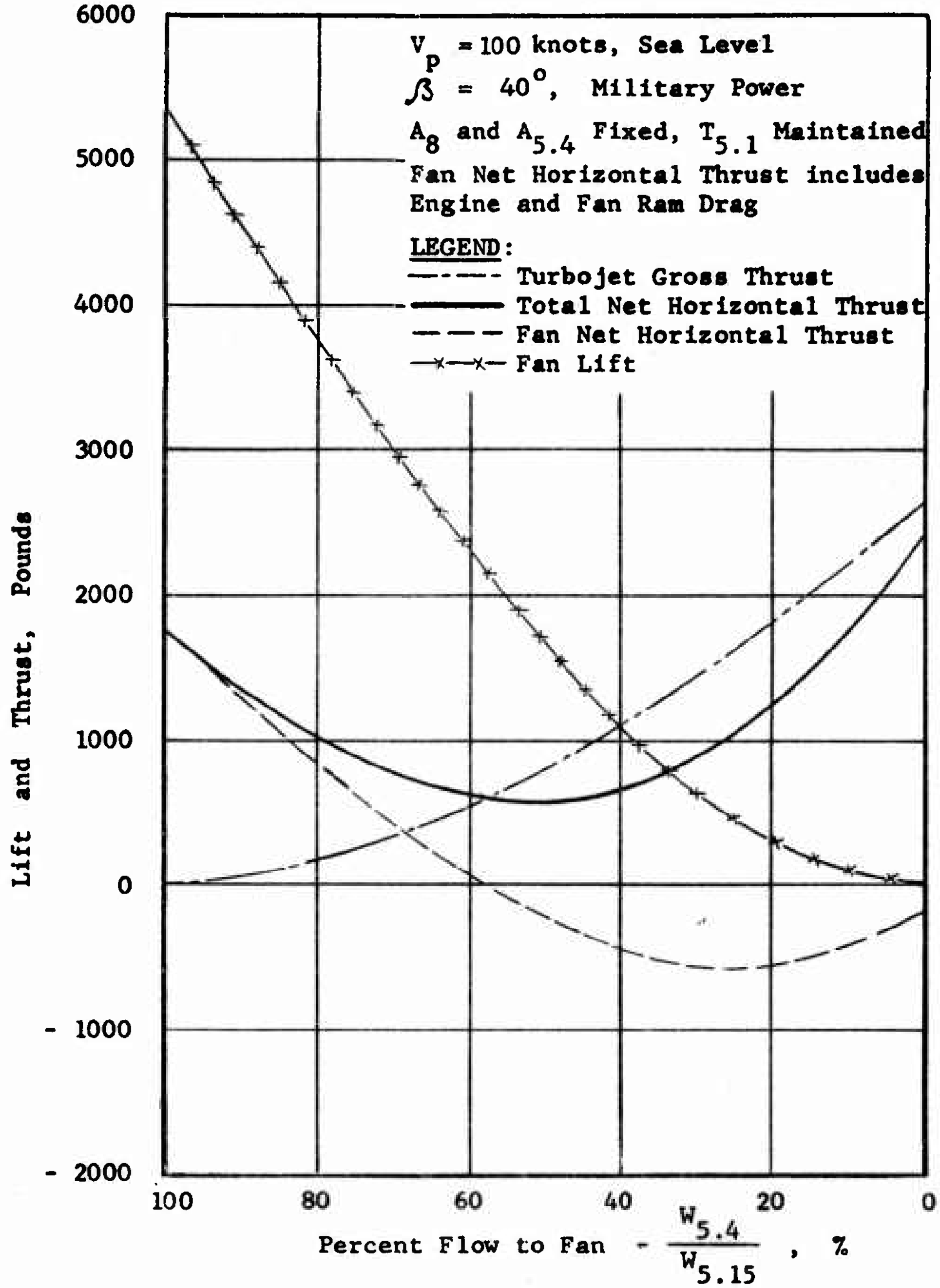


Figure 4 - Divided Flow Study (V_p = 100 knots)

X-353-5 Differential Diverter Valve Door Actuation

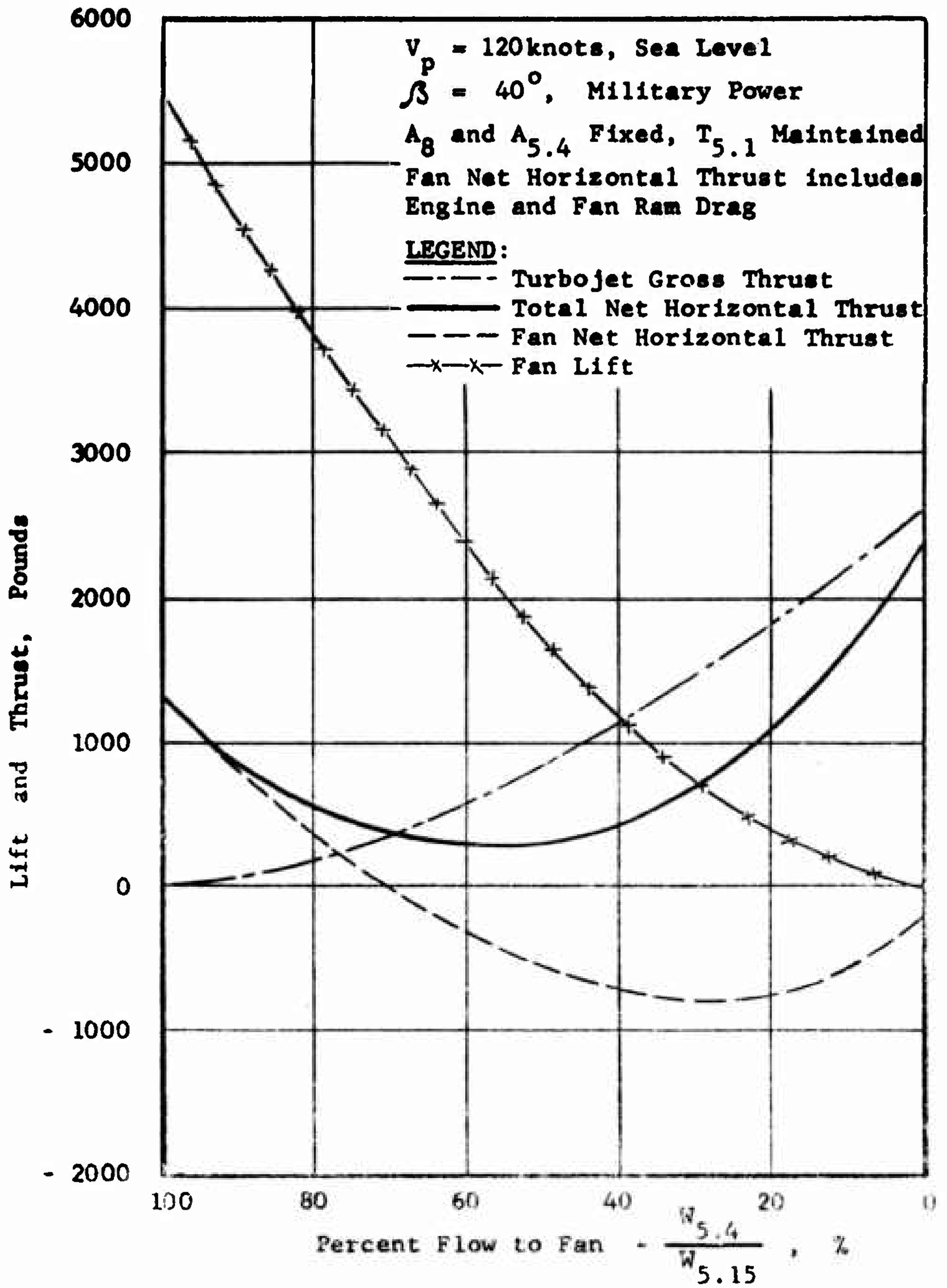


Figure 5 - Divided Flow Study (V_p = 120 knots)

X-353-5 Differential Diverter Valve Door Actuation

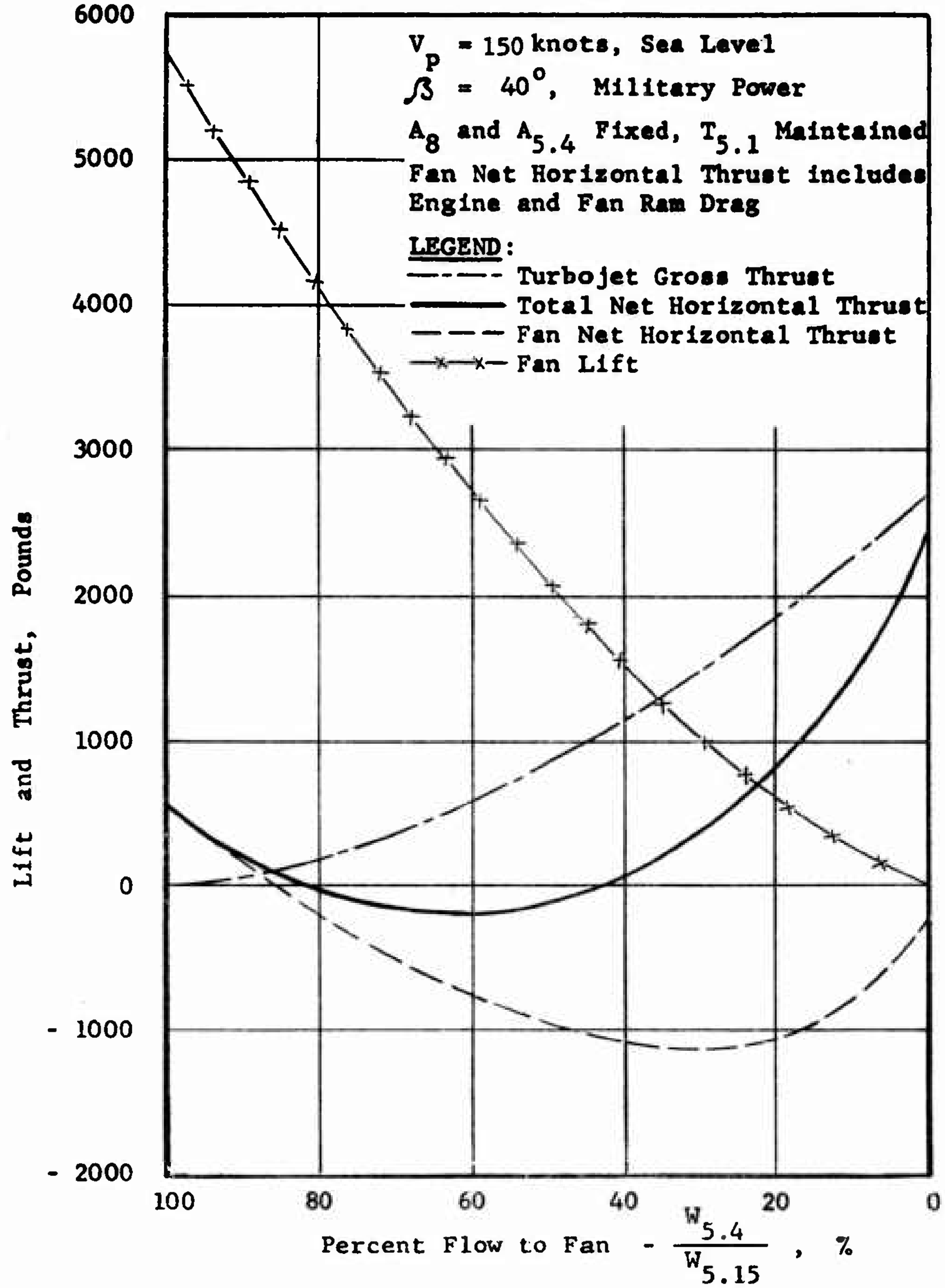


Figure 6 - Divided Flow Study (V_p = 150 knots)

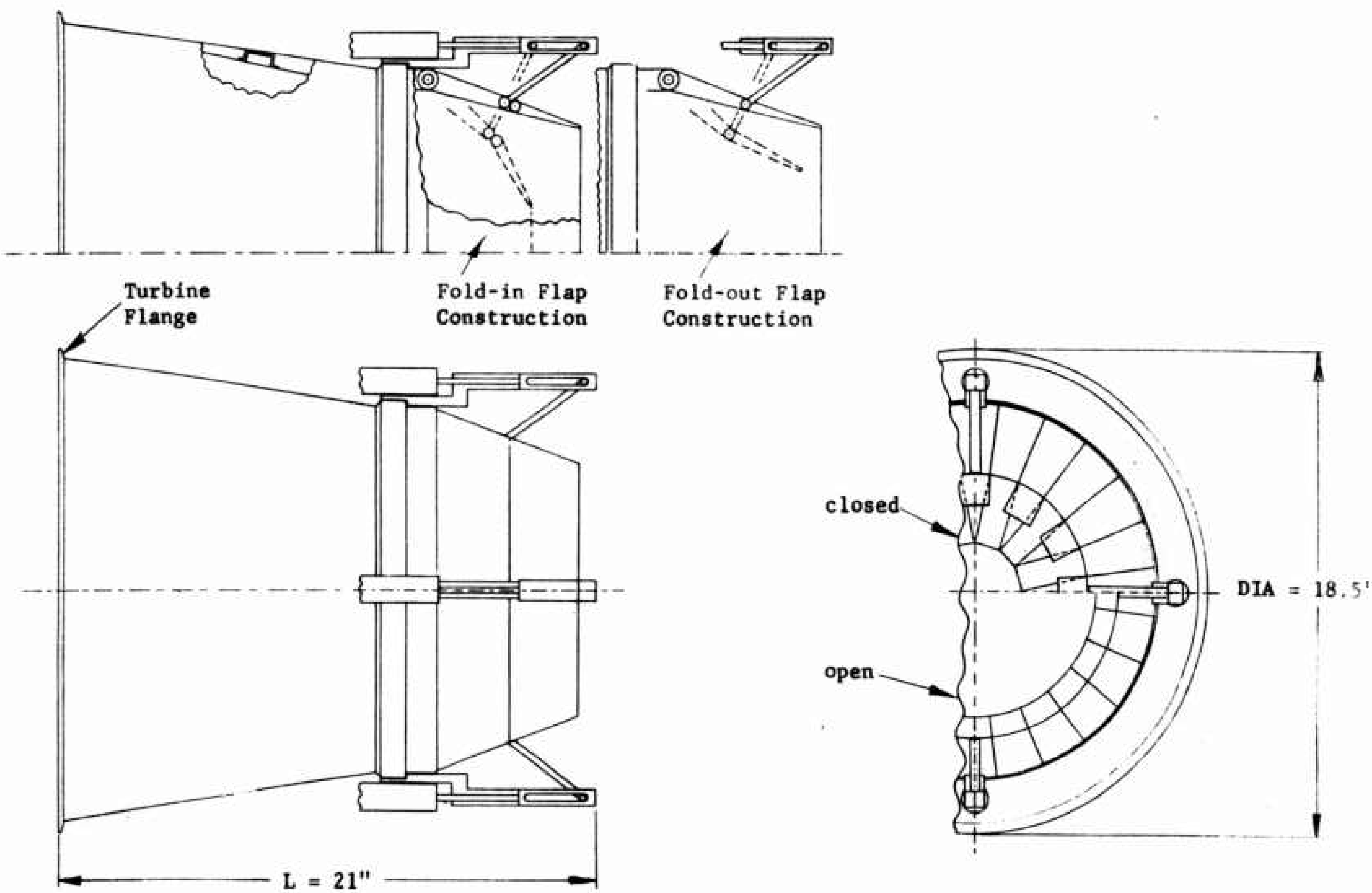


Figure 7 - Two-Flap Turbojet Nozzle

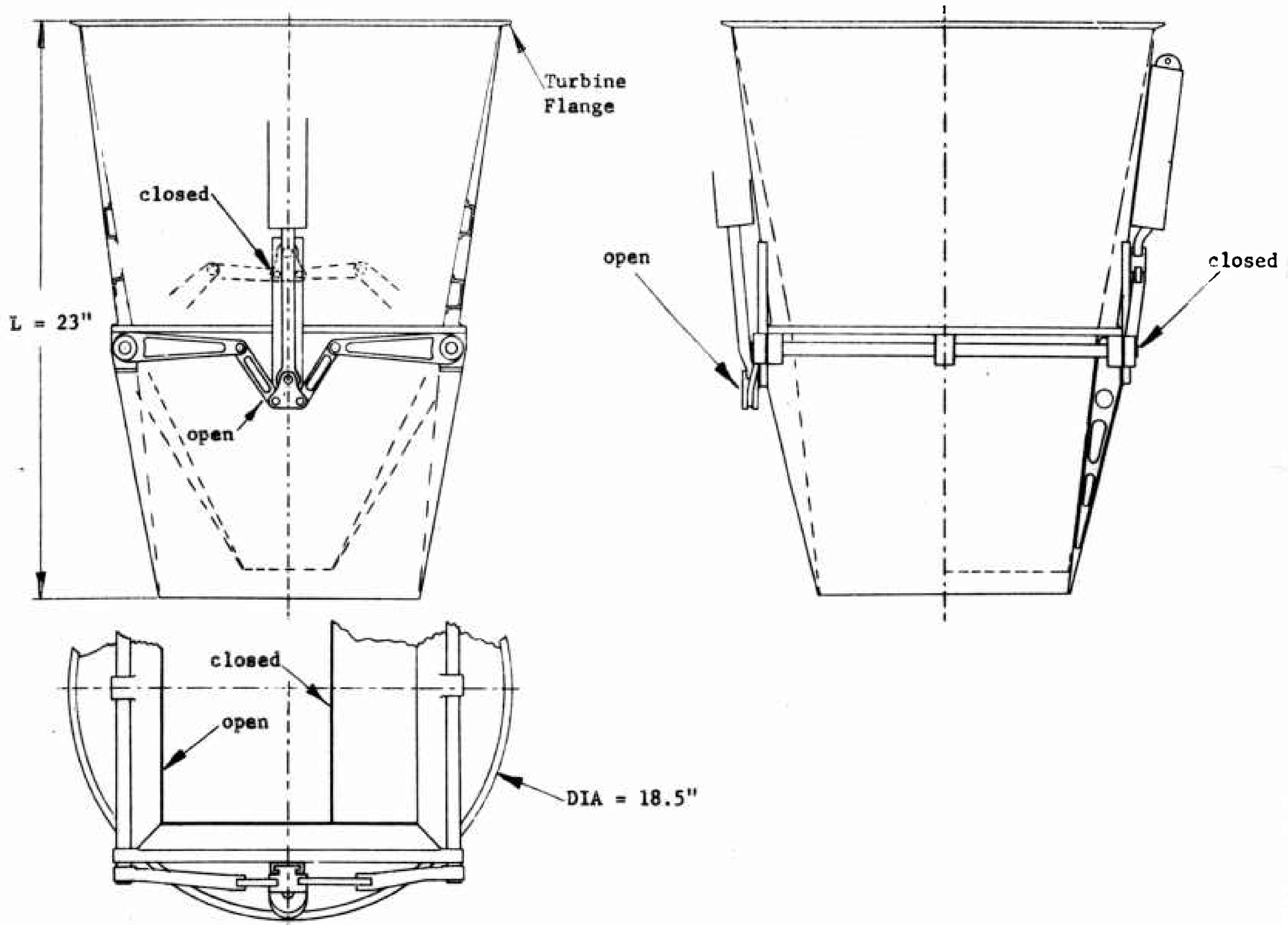


Figure 8 - Two-Flap Square Turbojet Nozzle

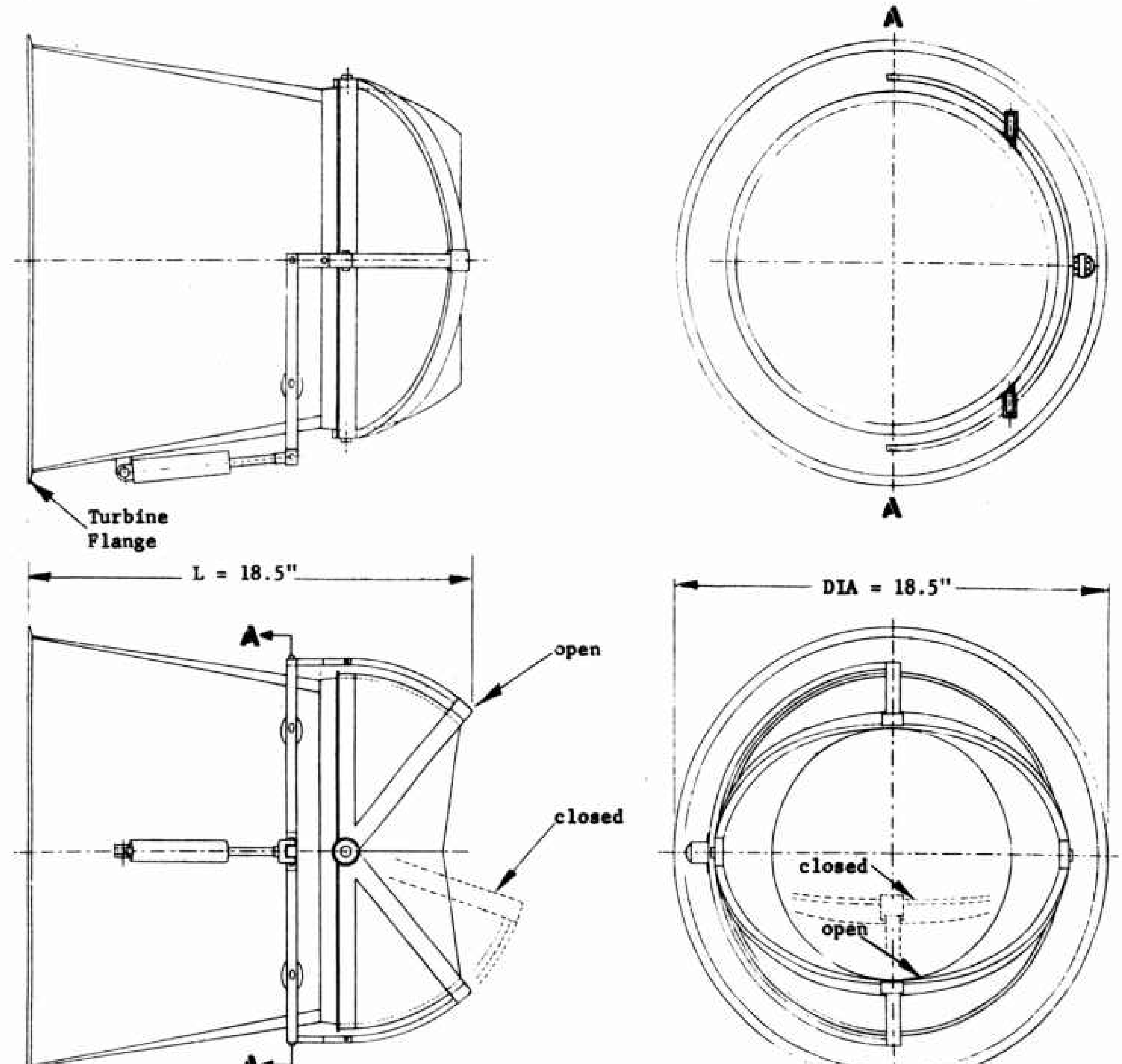


Figure 9 - Clamshell Turbojet Nozzle

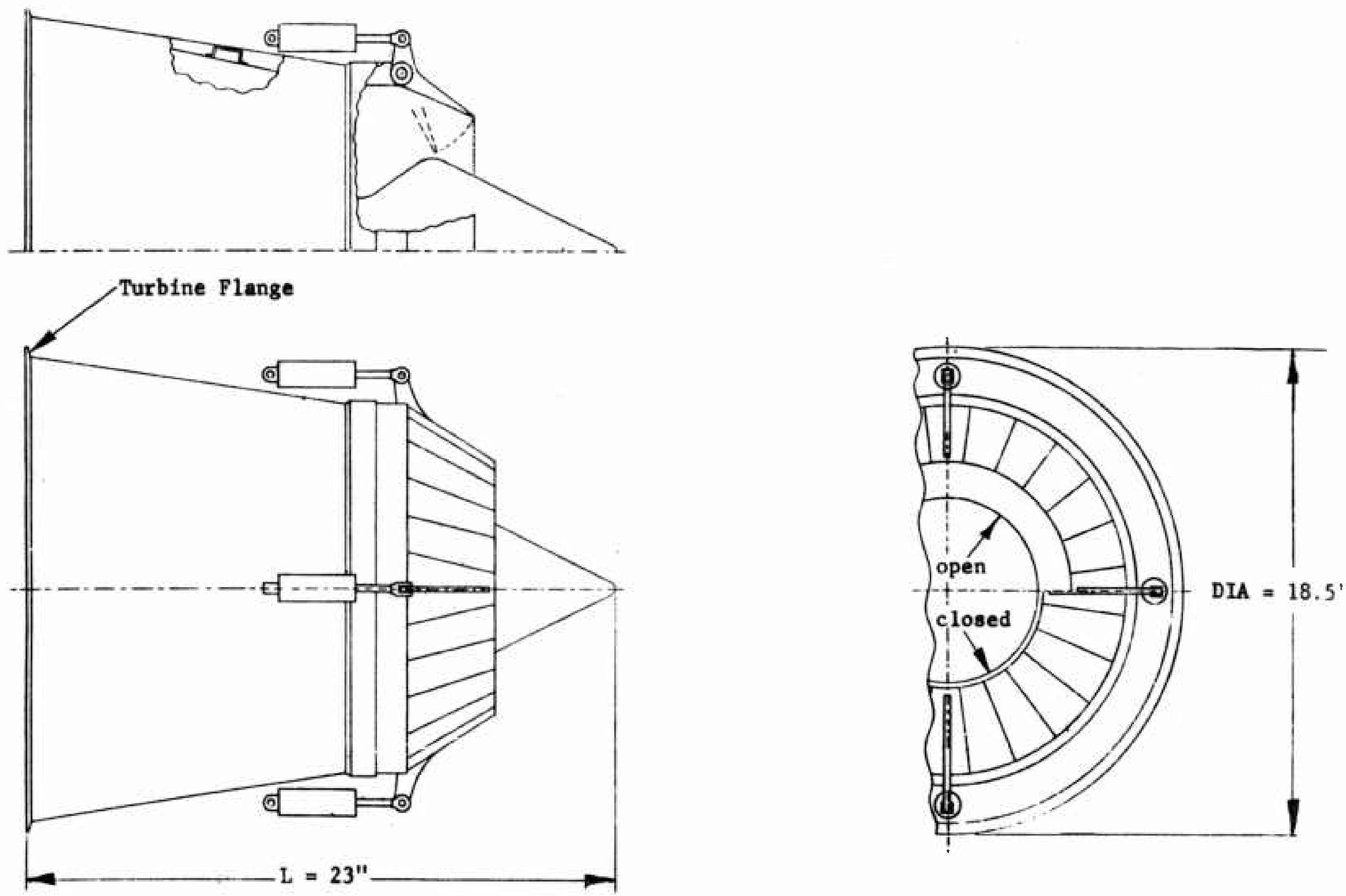
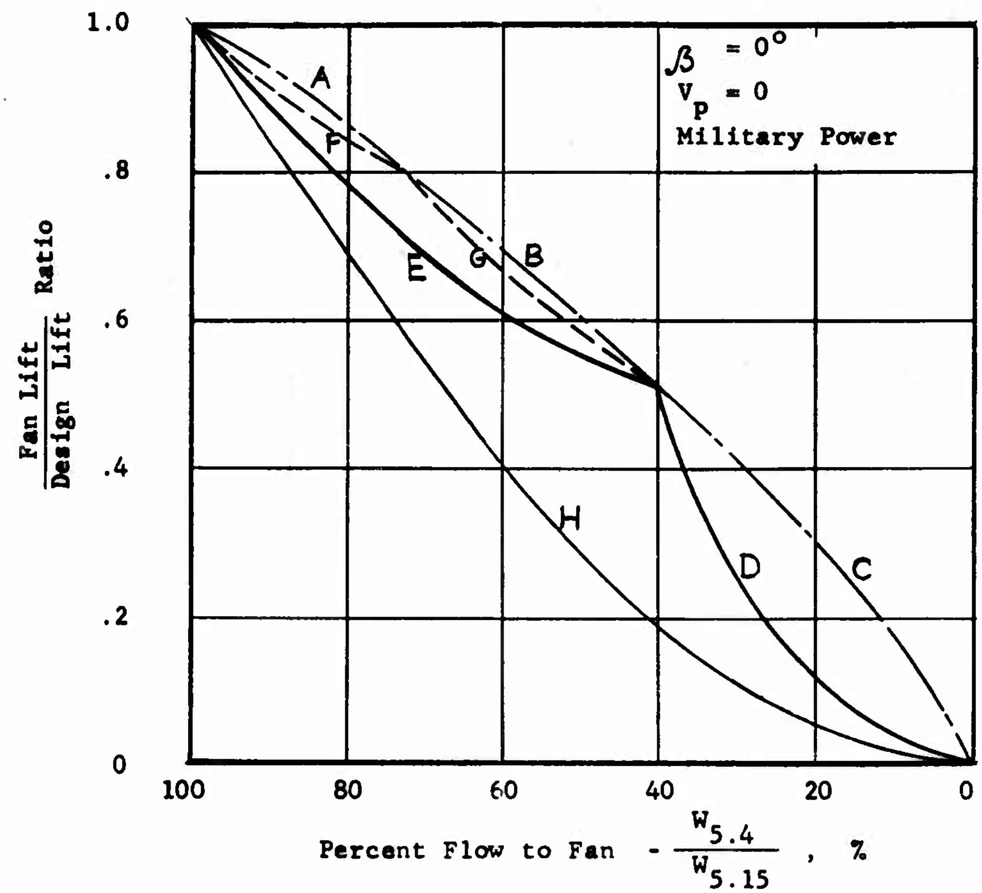
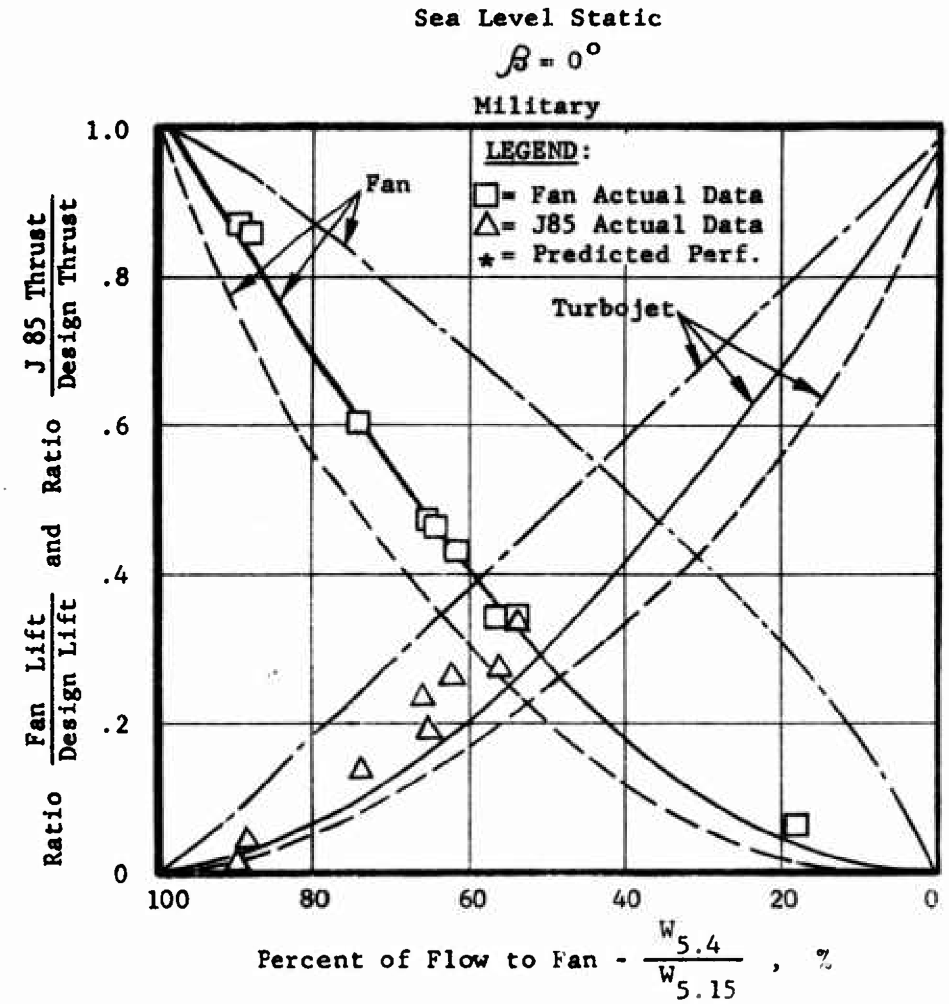


Figure 10 - Plug Nozzle with Flap Area Variation



VARIOUS METHODS OF FAN TURBINE
SCROLL NOZZLE AREA MODULATION

Figure 11 - Lift Ratio versus Flow Split



CASE	A_8	$A_{5.4}$	$T_{5.1}$	CURVE * LEGEND
Area Compensated	Variable	Variable	Maintained	— - — - —
Diverter Valve Doors Operated Separately	Fixed	Fixed	Maintained	————
Diverter Valve Doors Operated Together	Fixed	Fixed	Not Maintained	— — — —

Figure 12 - Full-Scale Test Results on Divided Flow Study

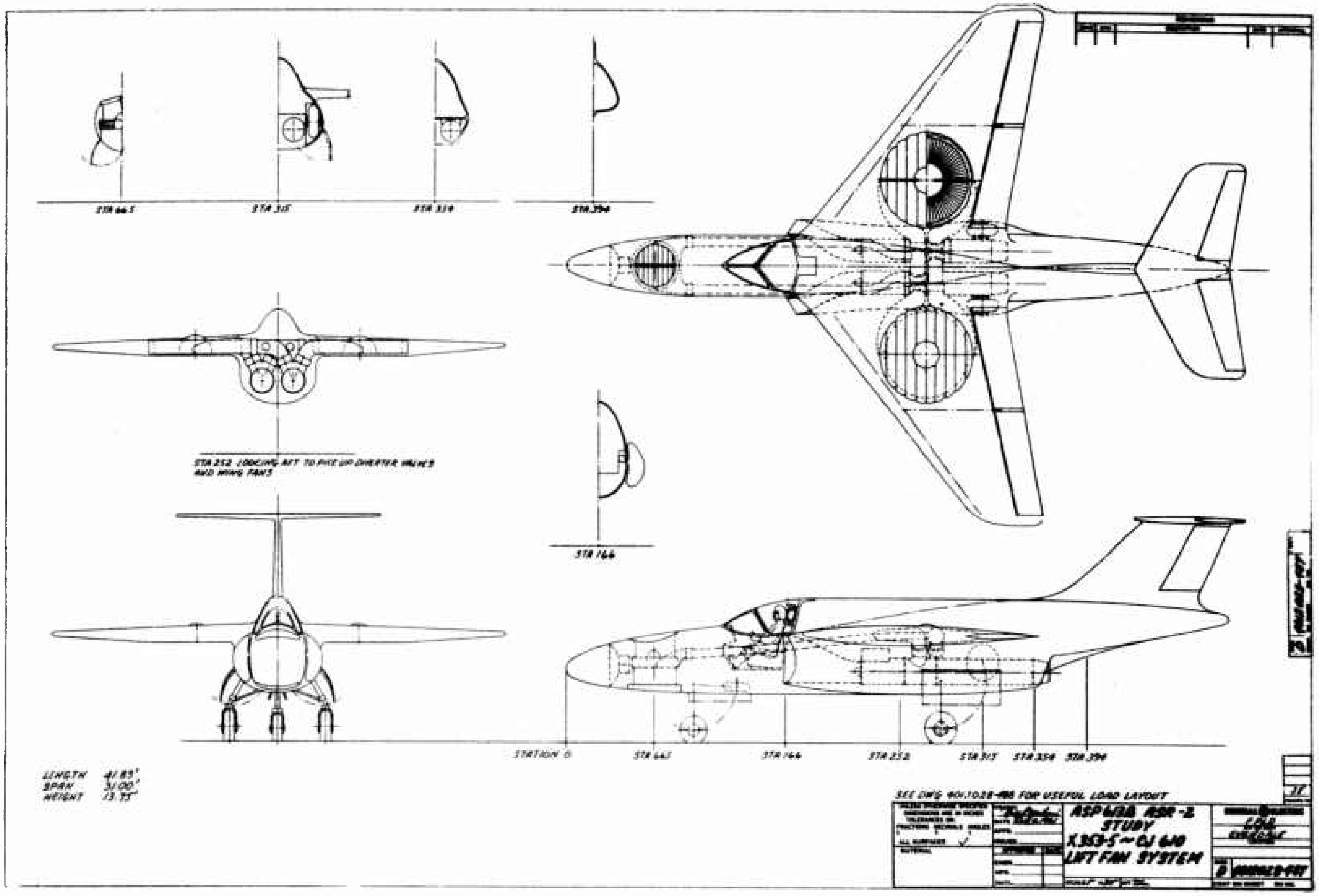
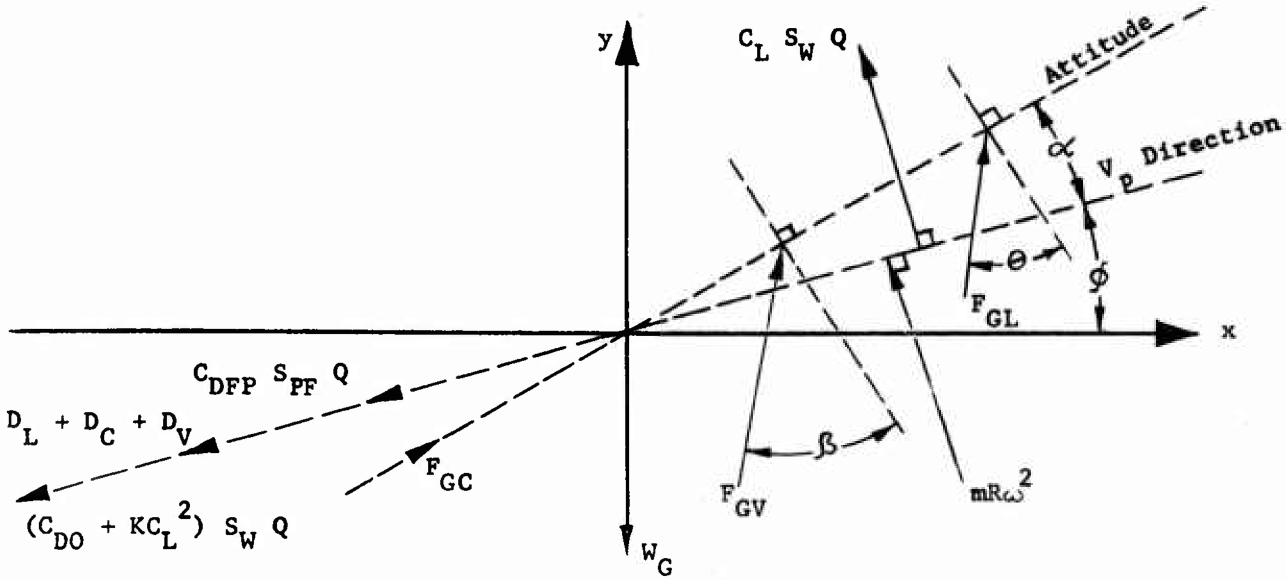


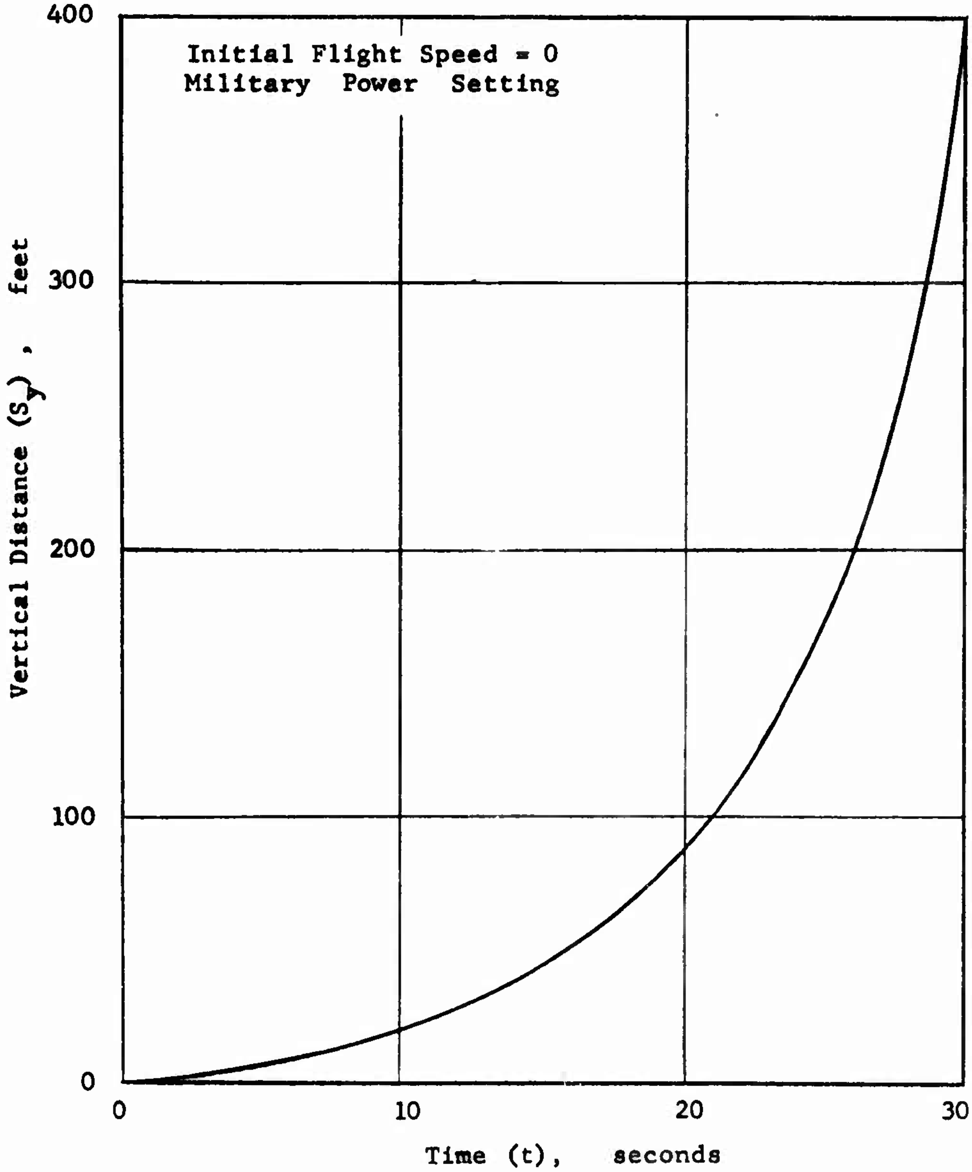
Figure 13 - ASP 613 B



$$ma_y = F_{GL}\cos(\theta - \phi - \alpha) + F_{GV}\cos(\beta - \phi - \alpha) - W_G + F_{GC}\sin(\phi + \alpha) - C_{DFP}\,S_{PF}\,Q\sin\phi - (C_{DO} + KC_L^{\ 2})\,S_W\,Q\sin\phi + C_L\,S_W\,Q\cos\phi + mR\omega^2\cos\phi - (D_L + D_V + D_C)\sin\phi$$

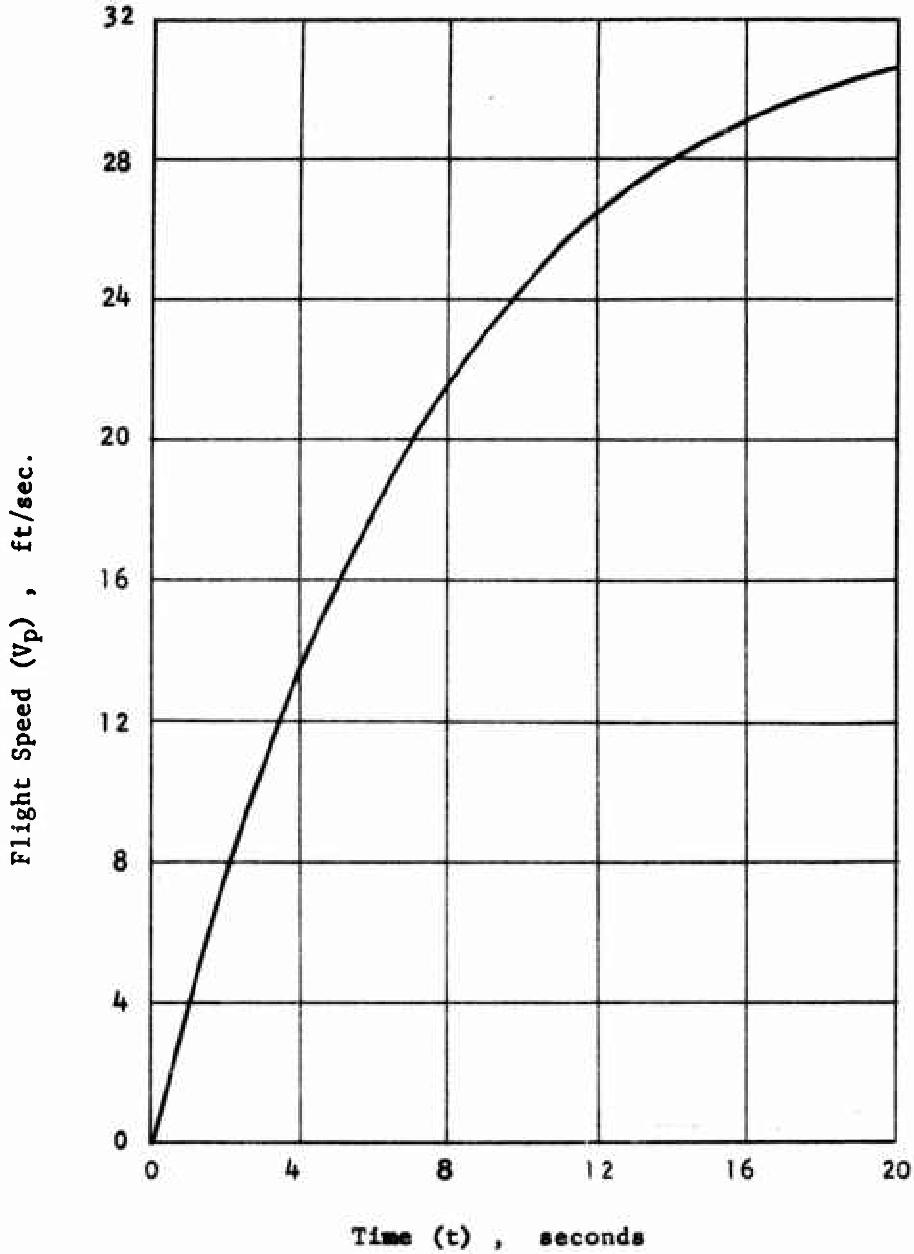
$$ma_x = F_{GL}\sin(\theta - \phi - \alpha) + F_{GV}\sin(\beta - \phi - \alpha) + F_{GC}\cos(\phi + \alpha) - C_{DPF}\,S_{PF}\,Q\cos\phi - (C_{DO} + KC_L^{\ 2})\,S_W\,Q\cos\phi - C_L\,S_W\,Q\sin\phi - mR\omega^2\sin\phi - (D_L + D_V + D_C)\cos\phi$$

Figure 14 - Transition Analysis Force Balance Diagram and Equations



TRANSITION REGIME I
VERTICAL CLIMB

Figure 15 - Vertical Distance vs Time



TRANSITION REGIME I
VERTICAL CLIMB

Figure 16 - Flight Speed versus Time

TRANSITION REGIME II
"HEEL-OVER"

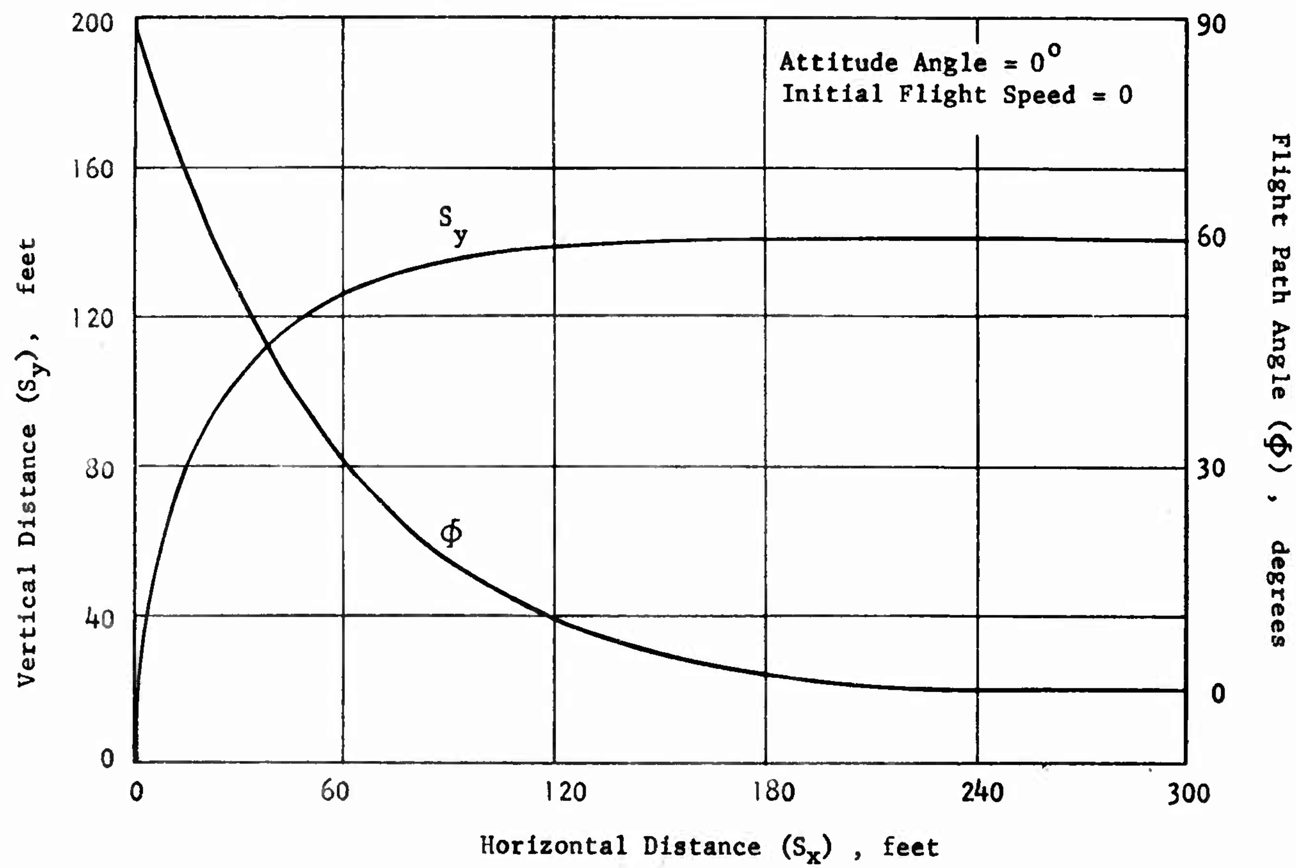


Figure 17 - Vertical Distance and Flight Path Angle versus Horizontal Distance

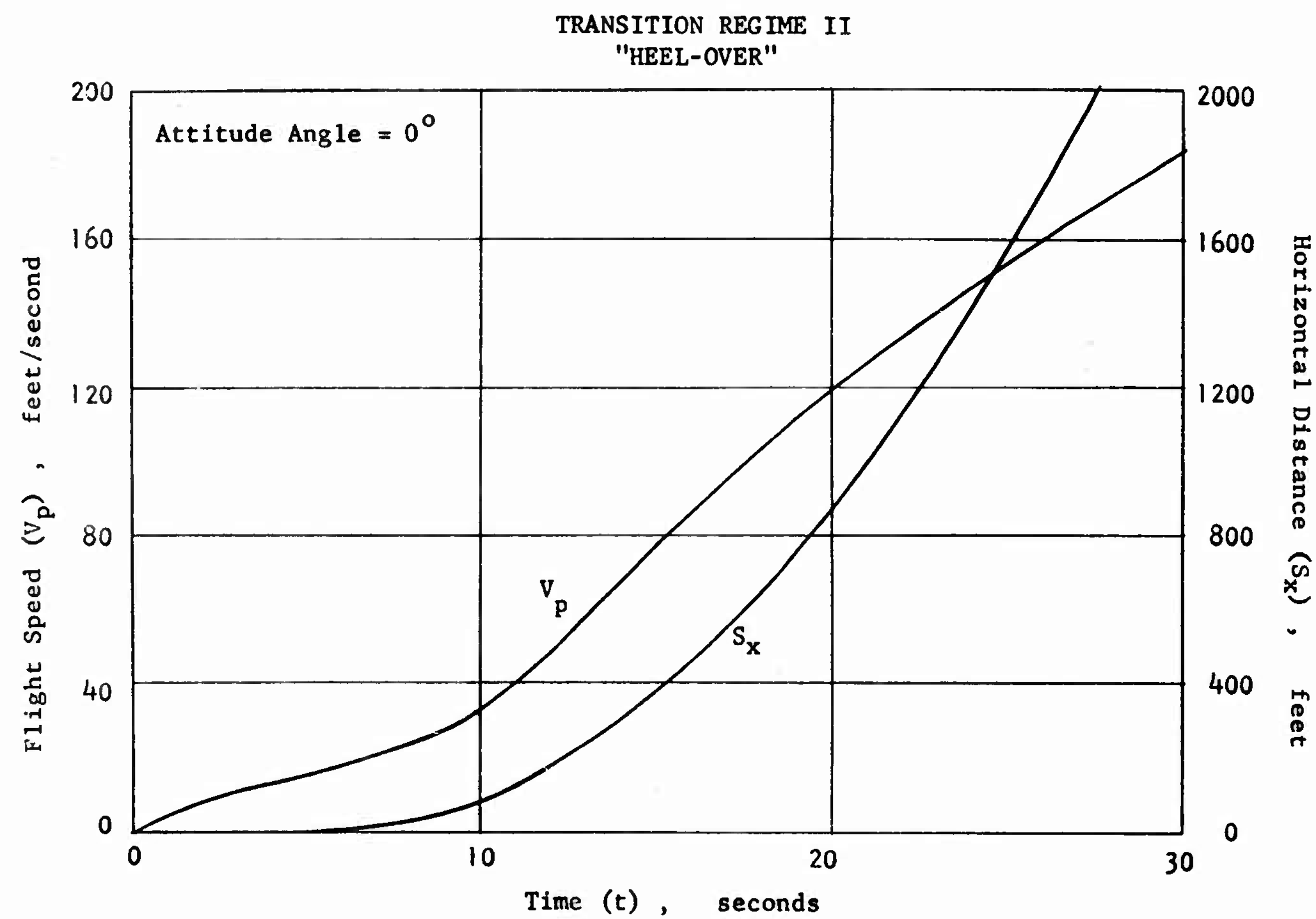


Figure 18 - Flight Speed and Horizontal Distance versus Time

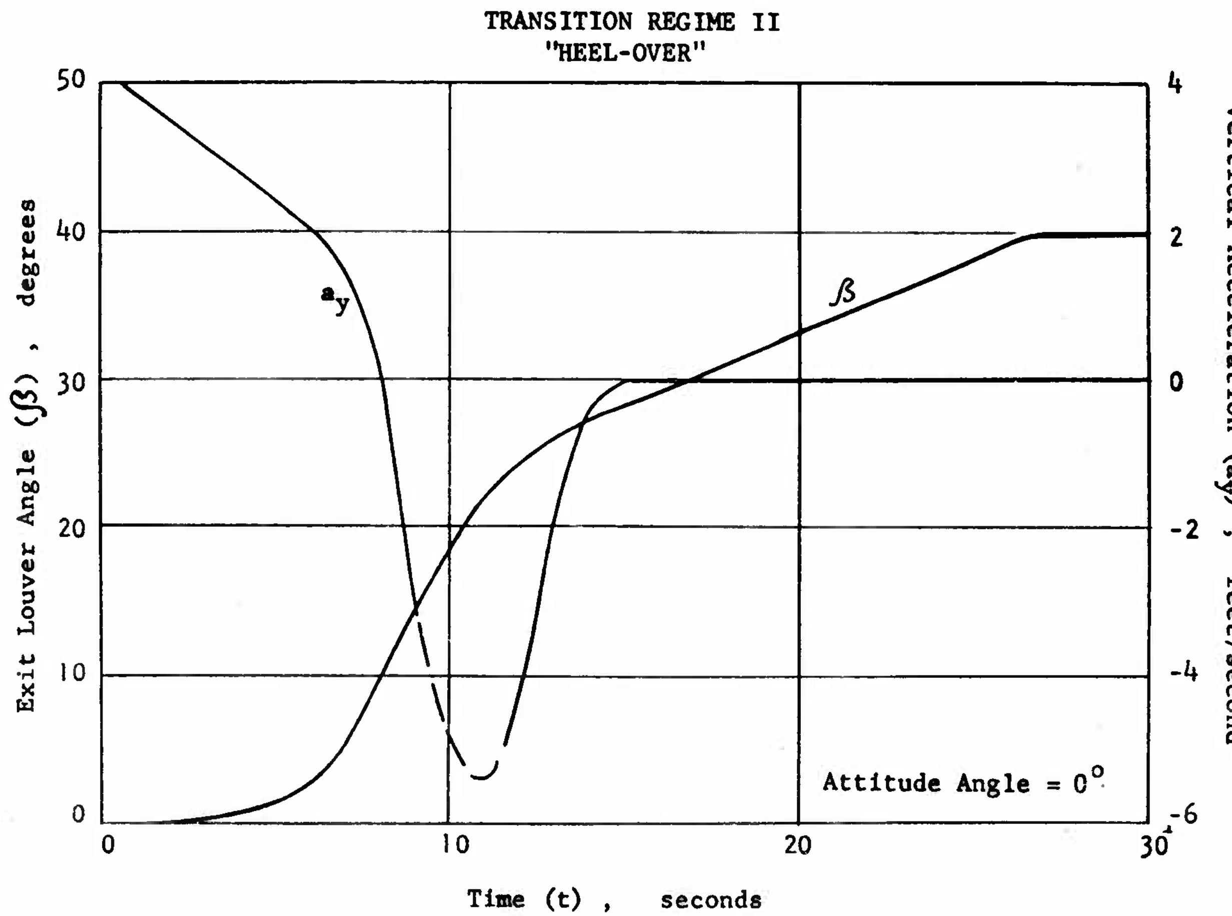
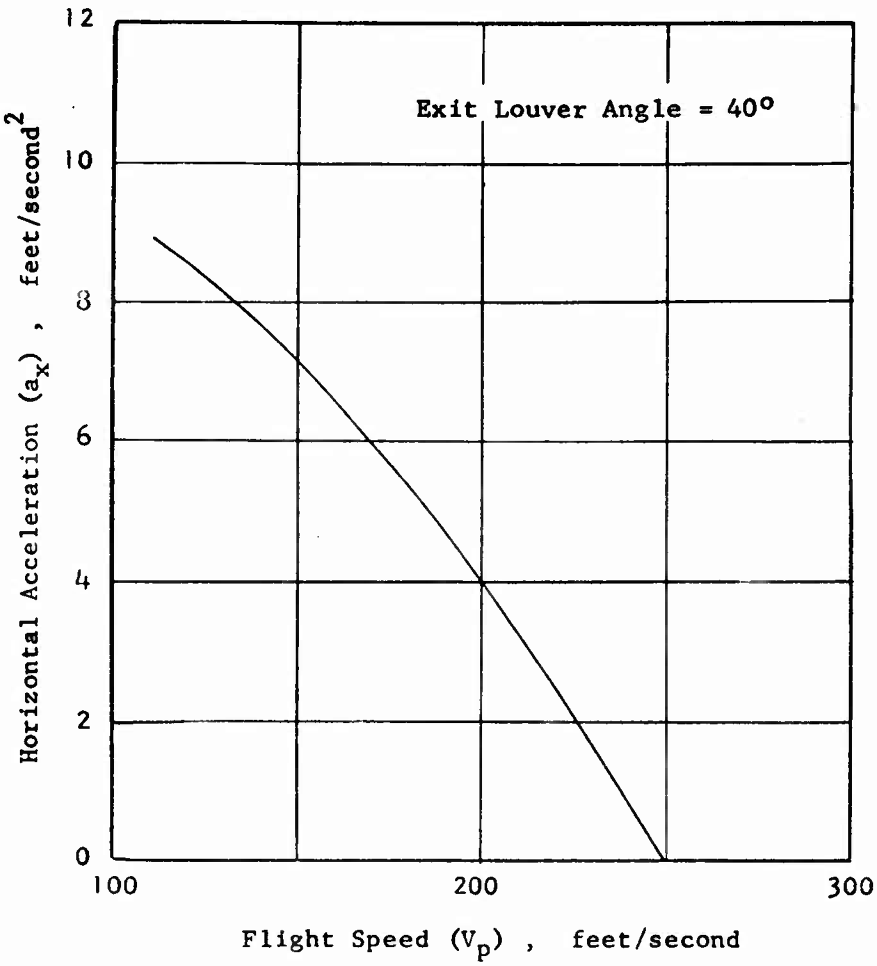


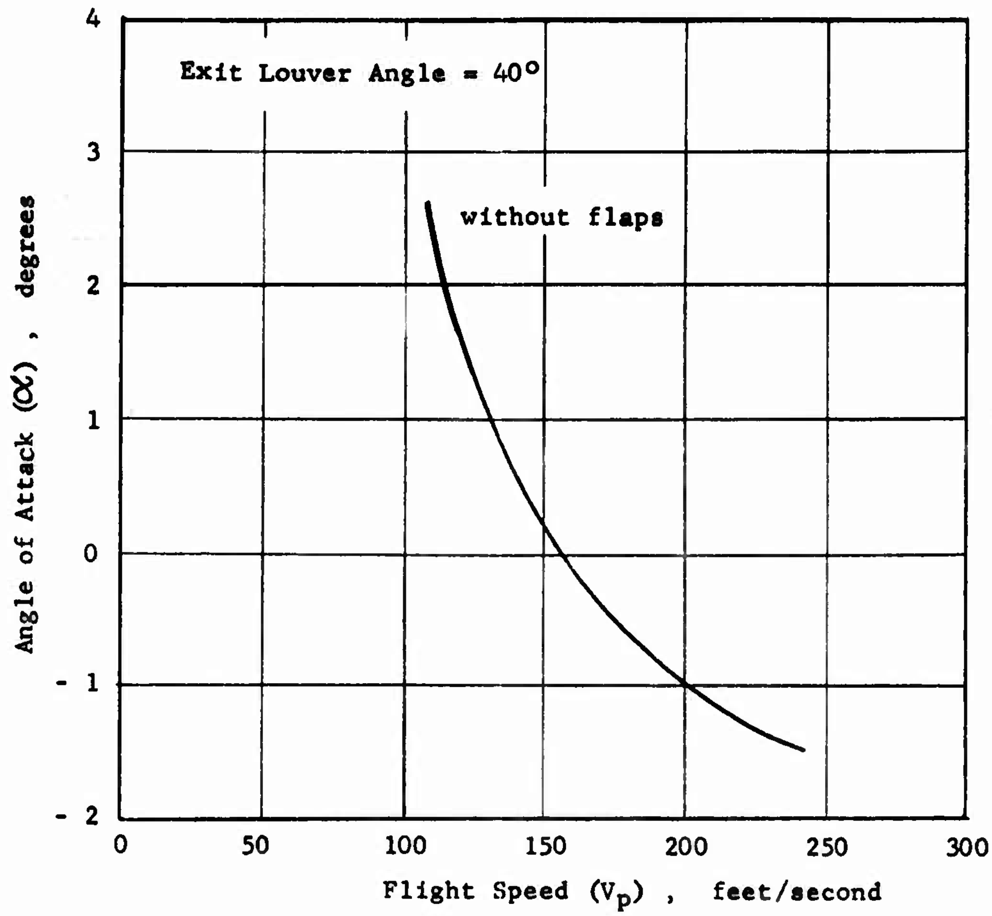
Figure 19 - Exit Louver Angle and Vertical Acceleration versus Time



TRANSITION REGIME III
ACCELERATION ON FANS

Horizontal Flight Path

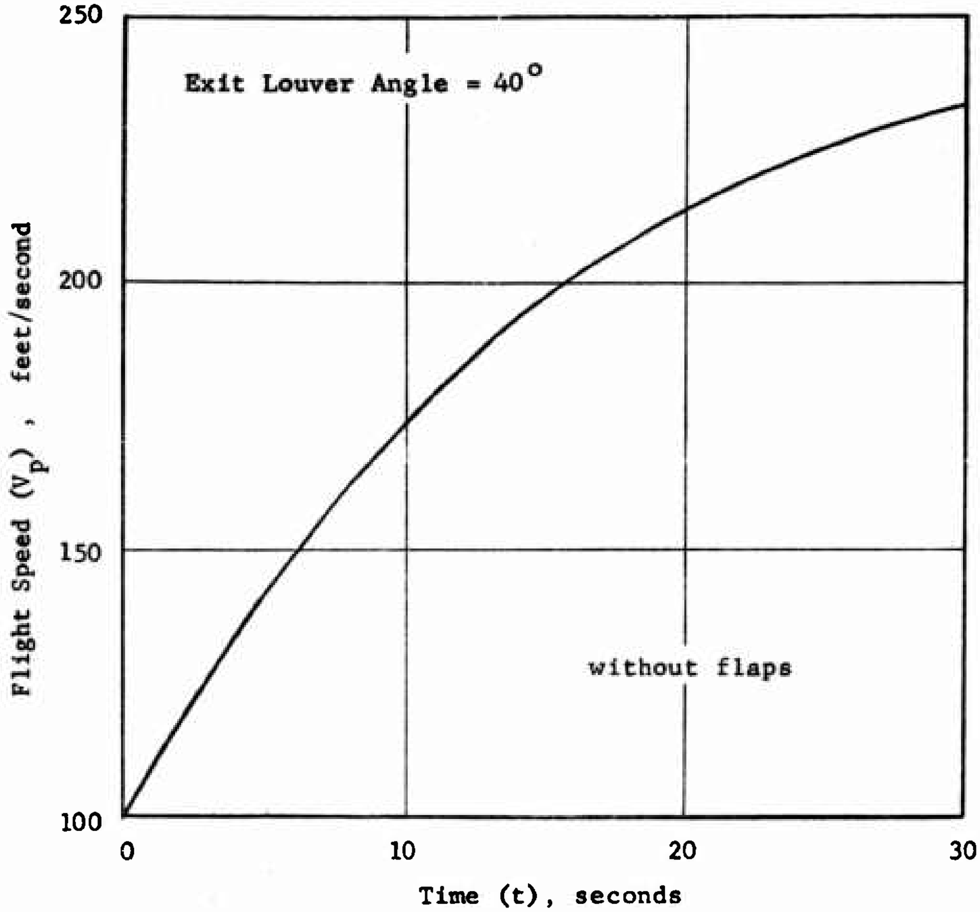
Figure 20 - Horizontal Acceleration versus Flight Speed



TRANSITION REGIME III
ACCELERATION ON FANS

Horizontal Flight Path

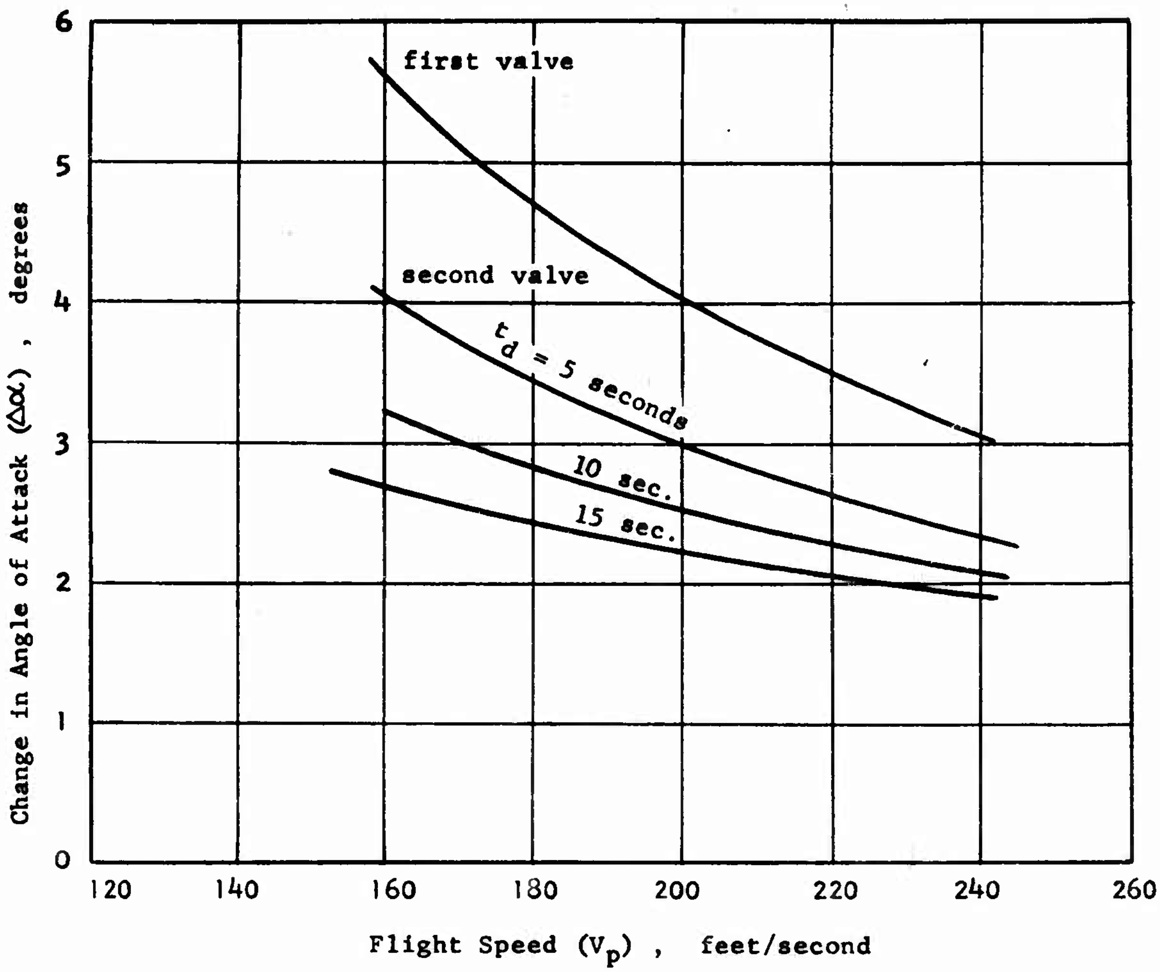
Figure 21 - Angle of Attack vs Flight Speed



TRANSITION REGIME III
ACCELERATION ON FANS

Horizontal Flight Path

Figure 22 - Flight Speed versus Time



TRANSITION REGIME IV
INSTANTANEOUS DIVERTER VALVE OPERATION

Horizontal Flight Path

Figure 23 - Change in Angle of Attack versus Flight Speed

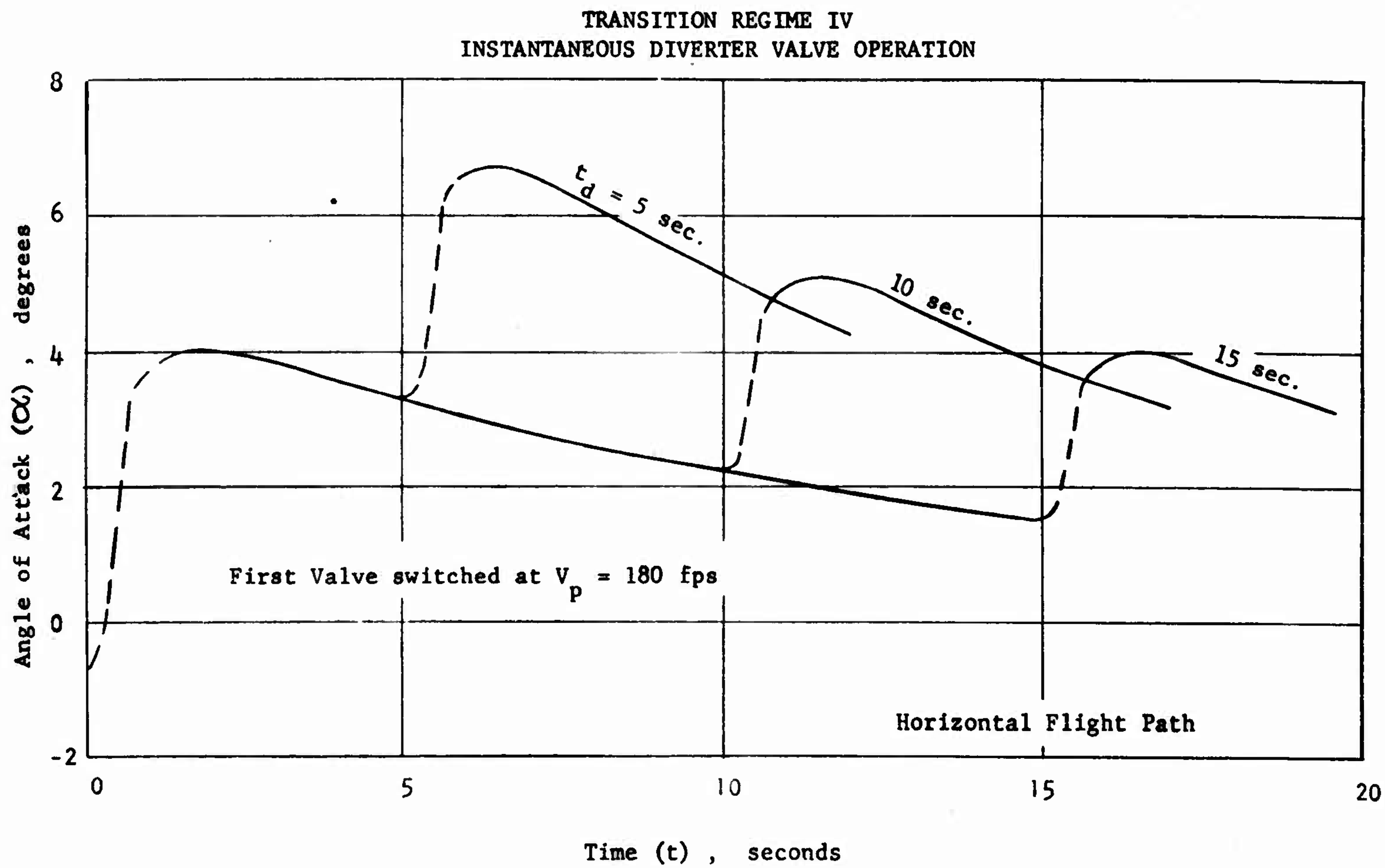


Figure 24 - Angle of Attack versus Time

TRANSITION REGIME IV
INSTANTANEOUS DIVERTER VALVE OPERATION

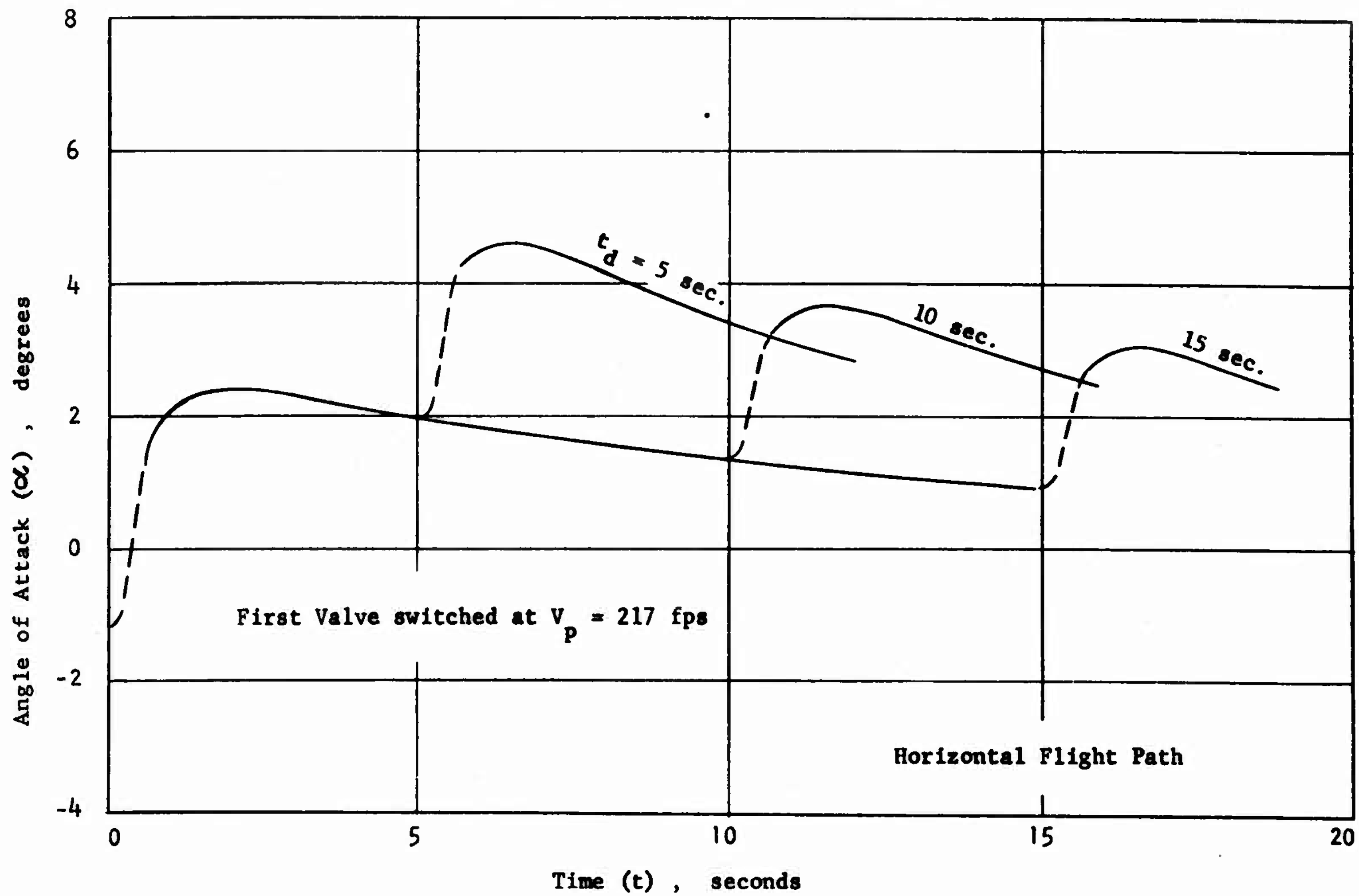


Figure 25 - Angle of Attach versus Time

TRANSITION REGIME IV
INSTANTANEOUS DIVERTER VALVE OPERATION

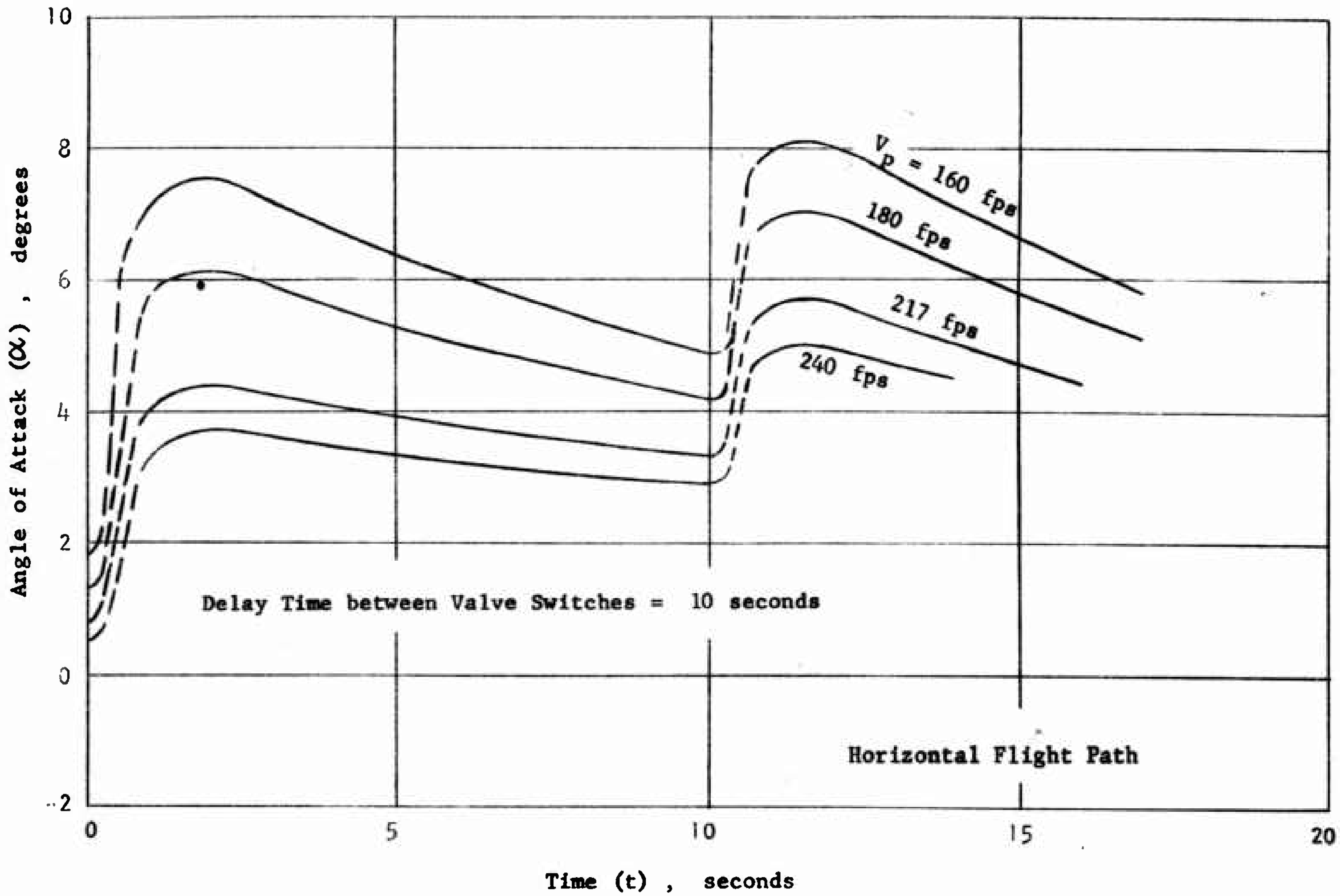
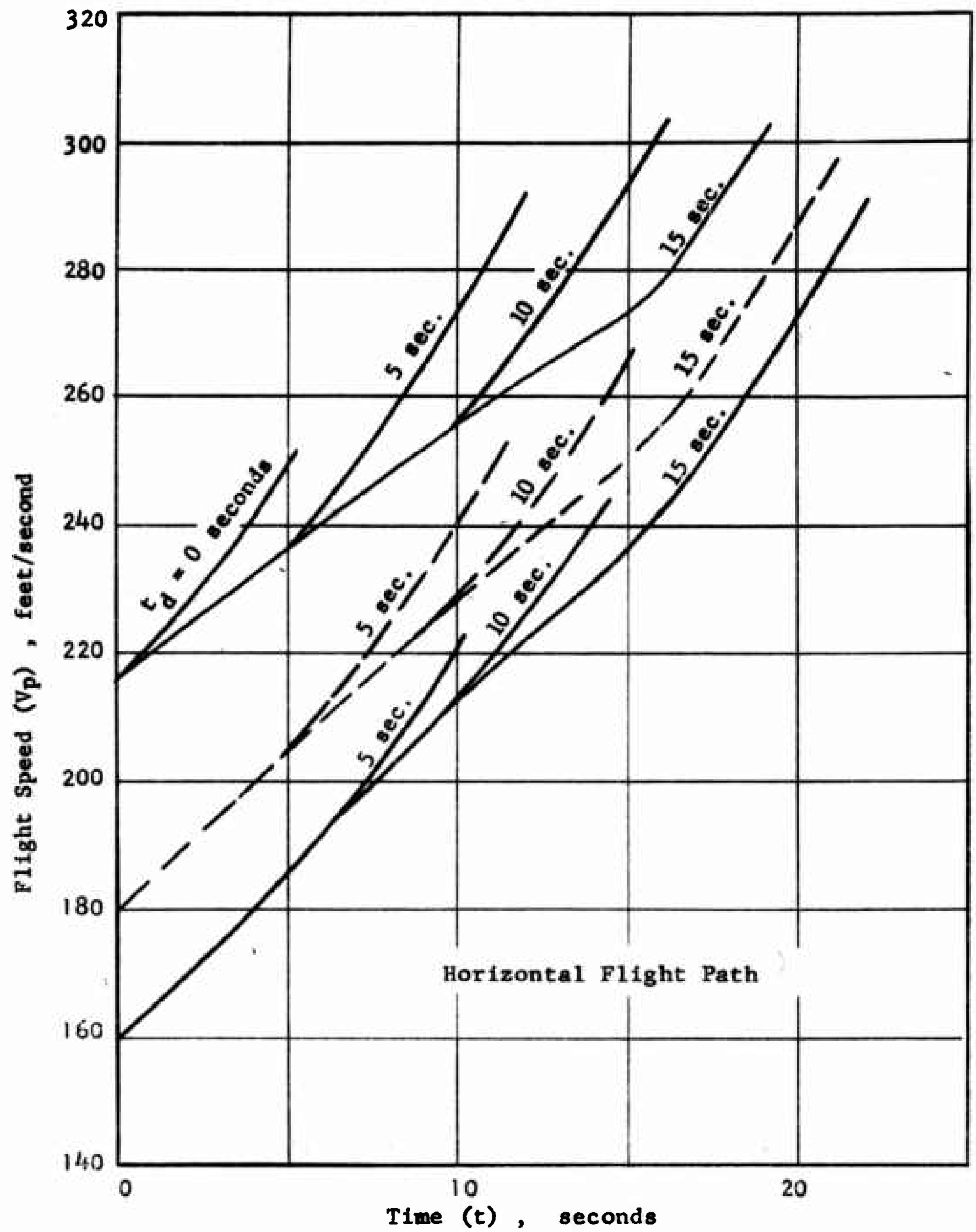
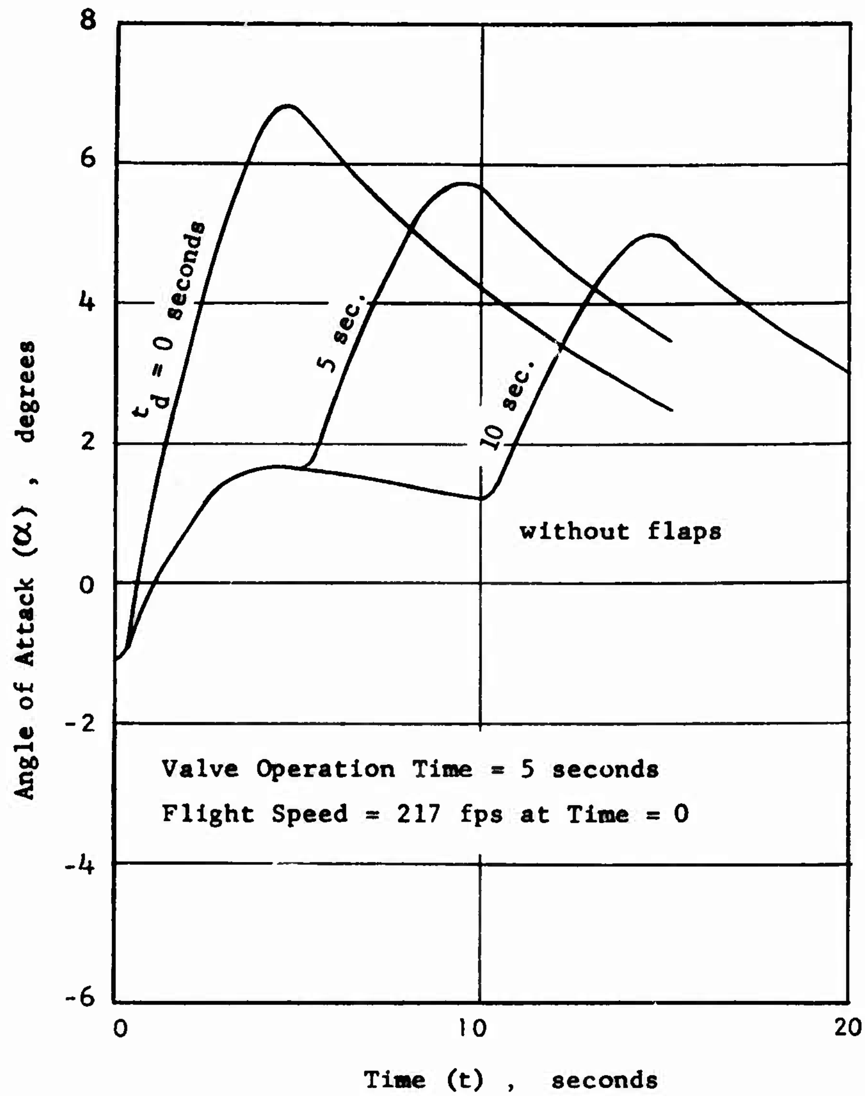


Figure 26 - Angle of Attack versus Time



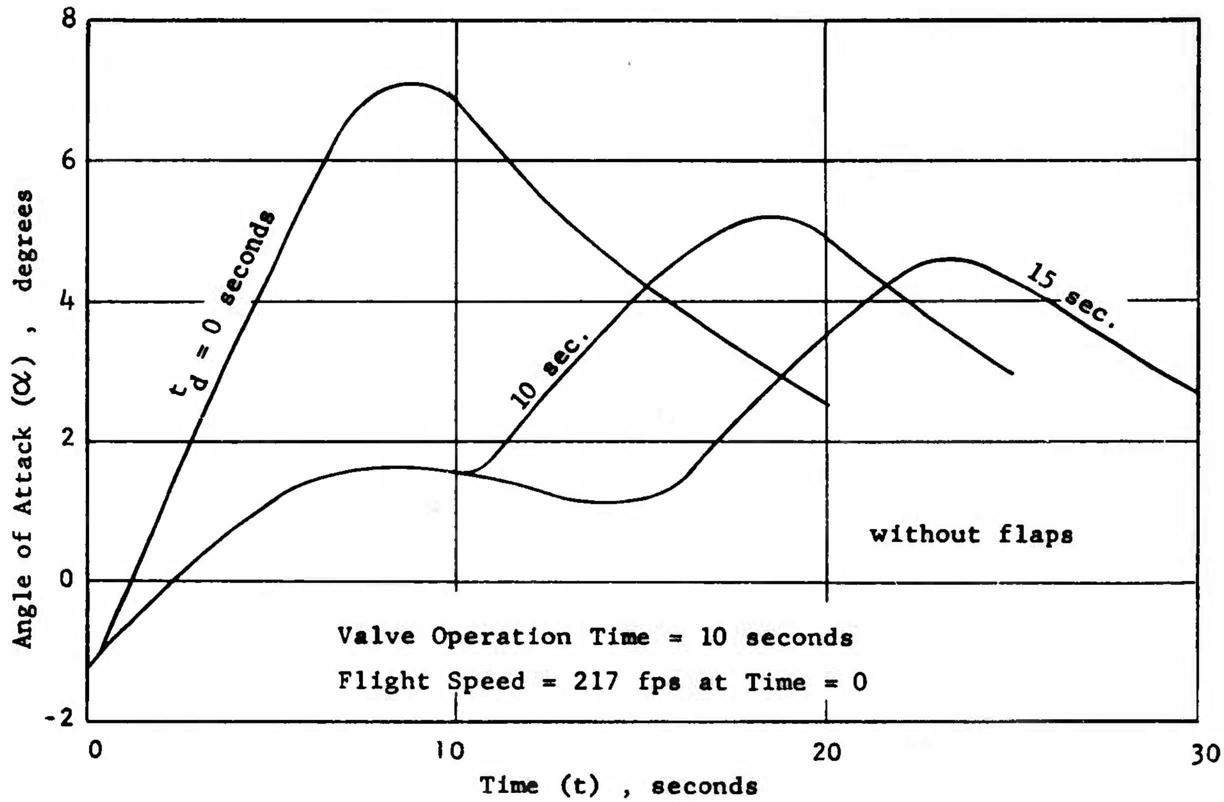
TRANSITION REGIME IV
INSTANTANEOUS DIVERTER VALVE OPERATION

Figure 27 - Flight Speed versus Time



TRANSITION REGIME IV
CONTROLLED DIVERTER VALVE OPERATION
Horizontal Flight Path

Figure 28 - Angle of Attack vs Time



TRANSITION REGIME IV
CONTROLLED DIVERTER VALVE OPERATION

Horizontal Flight Path

Figure 29 - Angle of Attack versus Time

TRANSITION REGIME IV
CONTROLLED DIVERTER VALVE OPERATION

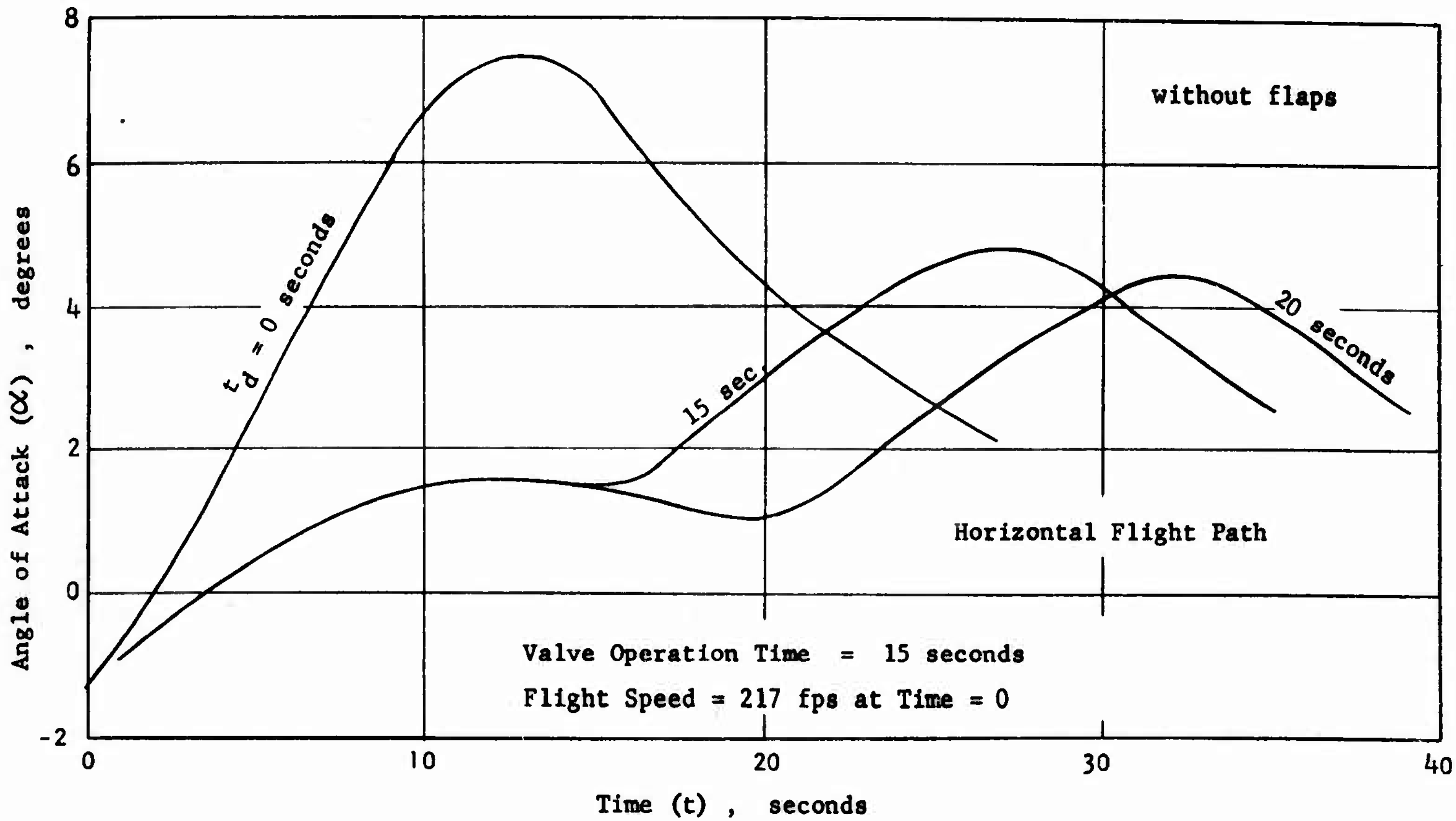
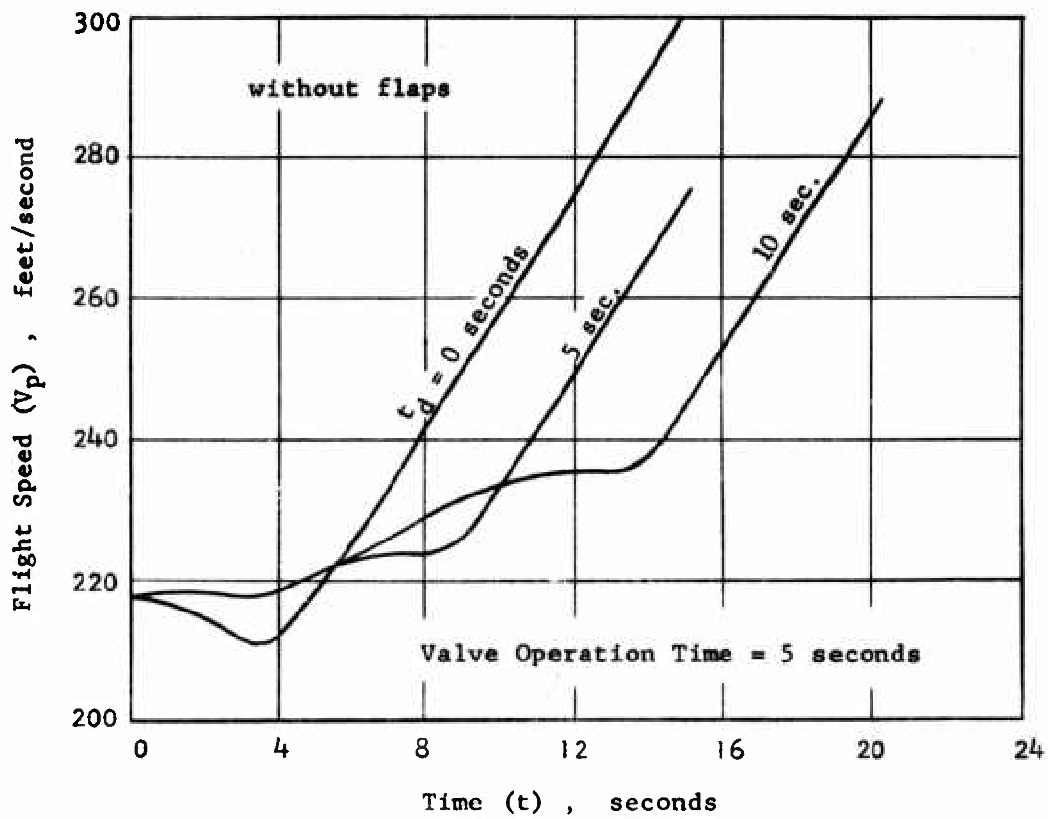


Figure 30 - Angle of Attack versus Time



TRANSITION REGIME IV
CONTROLLED DIVERTER VALVE OPERATION

Horizontal Flight Path

Figure 31 - Flight Speed versus Time

TRANSITION REGIME IV
CONTROLLED DIVERTER VALVE OPERATION

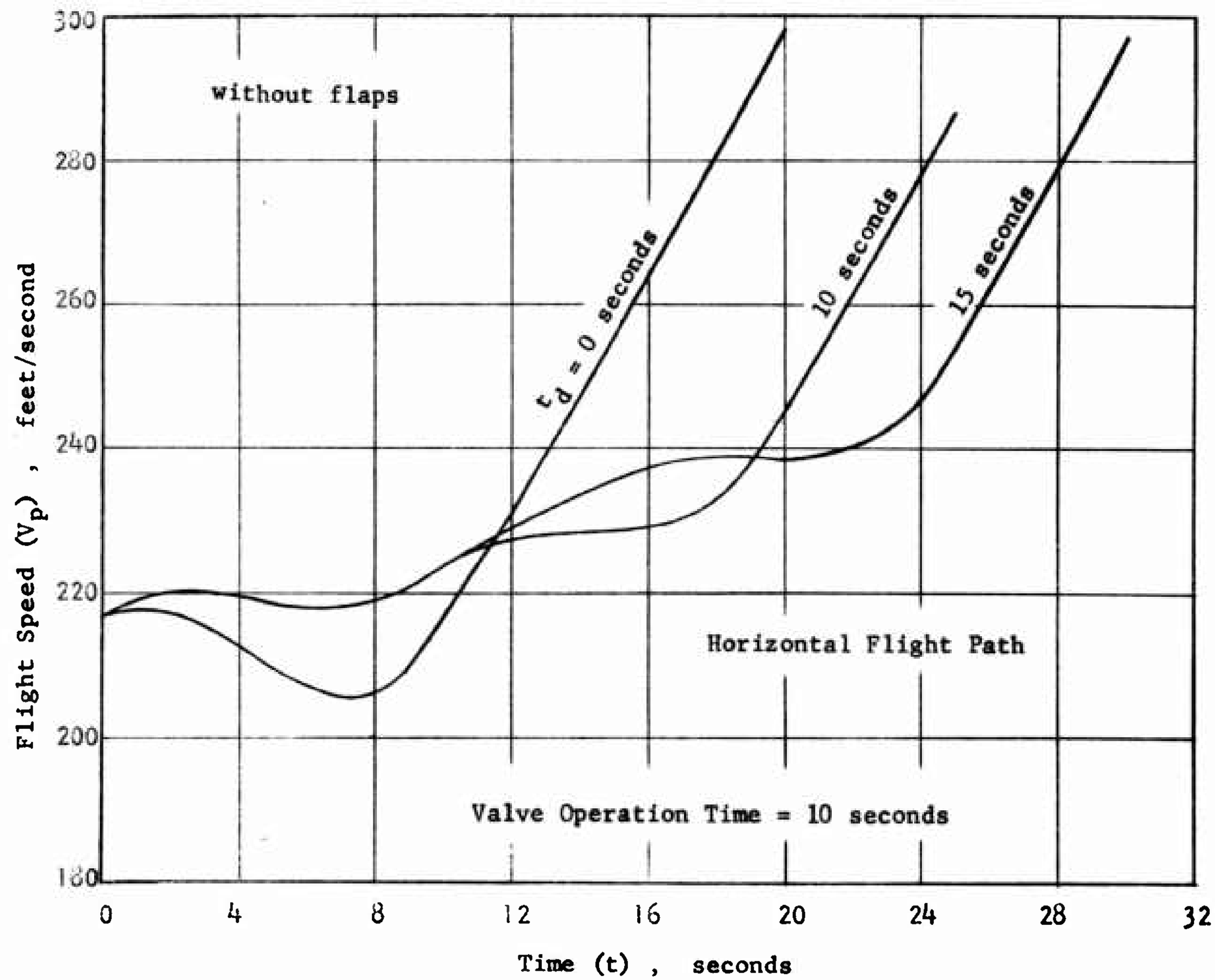


Figure 32 - Flight Speed versus Time

TRANSITION REGIME IV
CONTROLLED DIVERTER VALVE OPERATION

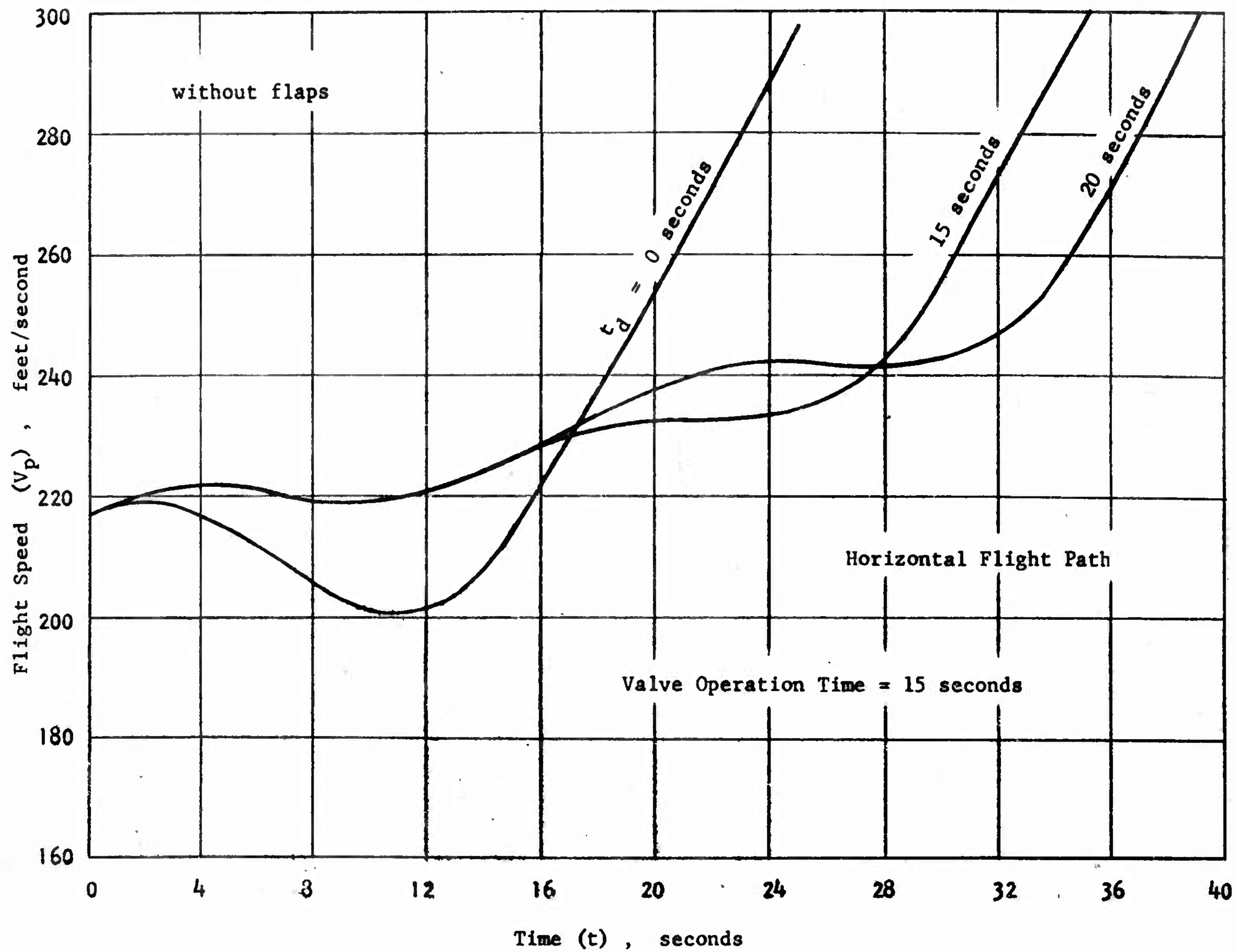


Figure 33 - Flights Speed versus Time

DISTRIBUTION

USCONARC	1
USAAVNBD	1
USATMC(FTZAT), ATO	1
ARO, Durham	2
OCRD, DA	1
CofT	2
USATMC	2
USATRECOM	33
AFSC (SCS-3)	1
Air Univ Lib	1
AFSC (Aero Sys Div)	2
ASD	2
CNR	2
BUWEPS, DN	2
USNPGSCH	1
USASGCA	1
Canadian LO, USATSCH	3
BRAS, DAQMG (Mov & Tn)	4
USASG, UK	1
Langley Rsch Cen, NASA	1
Ames Rsch Cen, NASA	2
Dav Tay Mod Bas	1
Lewis Rsch Cen, NASA	1
ASTIA	10
MOCOM	3
GE Co.	10

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GENERAL ELECTRIC COMPANY
Flight Propulsion Laboratory
Department
Cincinnati 15, Ohio

ANALYSIS AND TEST RESULTS
OF DIVISION OF POWER
BETWEEN LIFT FAN AND JET NOZZLE

Three methods of dividing engine power between a lift fan and jet nozzle for improved vertical to horizontal flight transition capability are analized. These methods are: (1) gas generator discharge area not maintained (fixed fan turbine and jet (over)

Unclassified

1. VTOL Aircraft Propulsion

   Dividing Engine Power between Lift Fan and Jet Nozzle for improved Vertical to Horizontal Flight Transition.

2. Contract DA 44-177-TC-584

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2. Contract DA 44-177-TC-584

nozzle areas, fixed diverter valve door relative position). (2) gas generator discharge area maintained by diverter valve (fixed fan turbine and jet nozzle areas, variable diverter valve door relative position), and (3) gas generator discharge area maintained by turbine and jet nozzles (fan turbine and jet nozzle areas variable, fixed diverter valve door relative position). Designs for accomplishing the above with minimum modification of X353-5 and current diverter valve design are presented and compared on a weight and performance basis.

Test results verifying variable diverter valve door relative position methods are presented.

Aircraft transition performance using the above results is presented.

Diverter valve door area control is the best method based on weight, complexity and acceptable transition performance.

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Unclassified

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UNCLASSIFIED

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